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Geisberger

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(54) **MEMS GYROSCOPE DEVICE**

(71) Applicant: **FREESCALE SEMICONDUCTOR, INC.**, Austin, TX (US)

(72) Inventor: **Aaron A. Geisberger**, Austin, TX (US)

(73) Assignee: **NXP USA, Inc.**, Austin, TX (US)

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G01C 19/5747 (2012.01)

(52) **U.S. Cl.**
CPC ***G01C 19/5747*** (2013.01)

(58) **Field of Classification Search**
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USPC 73/504.12
See application file for complete search history.

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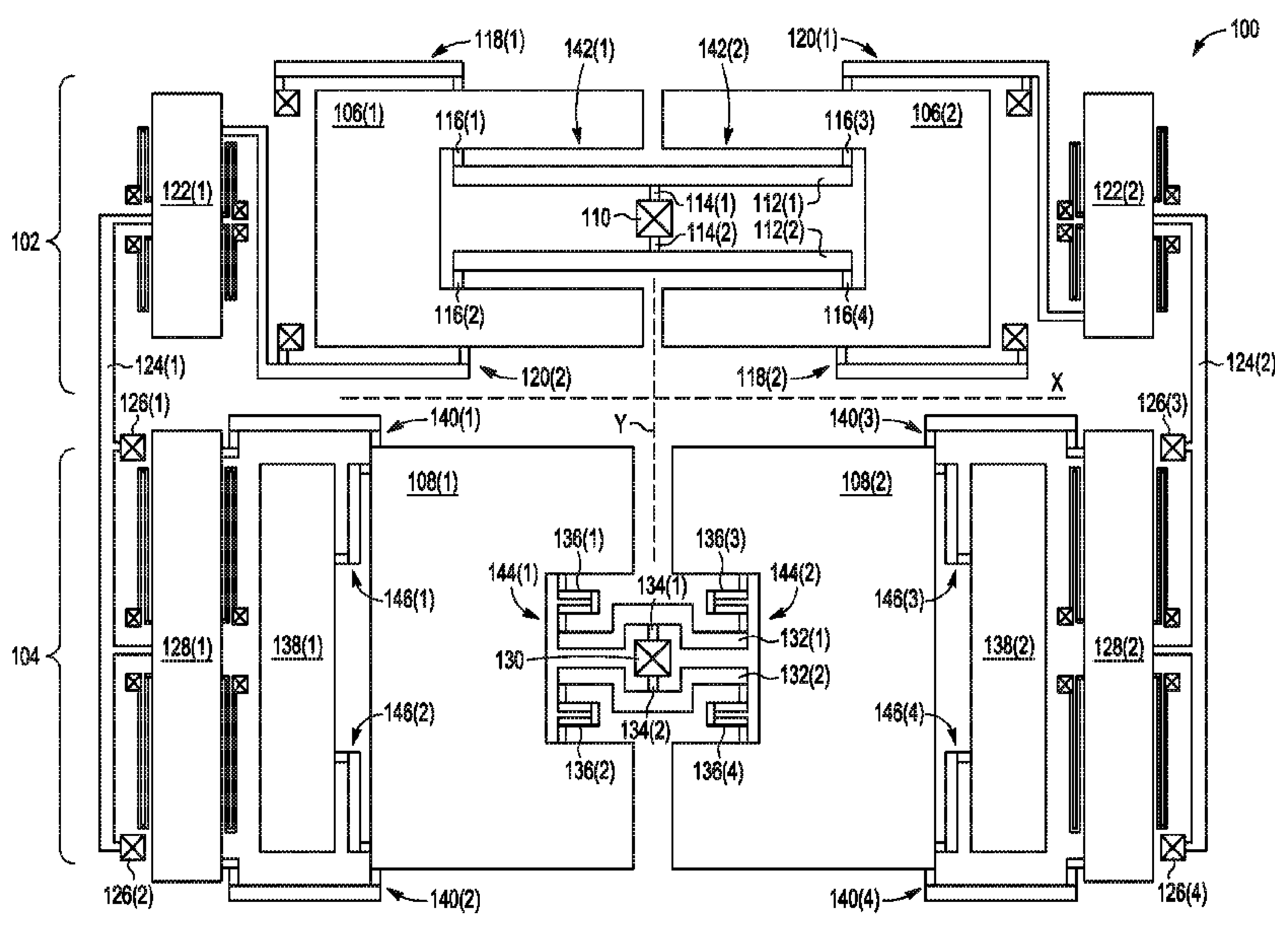
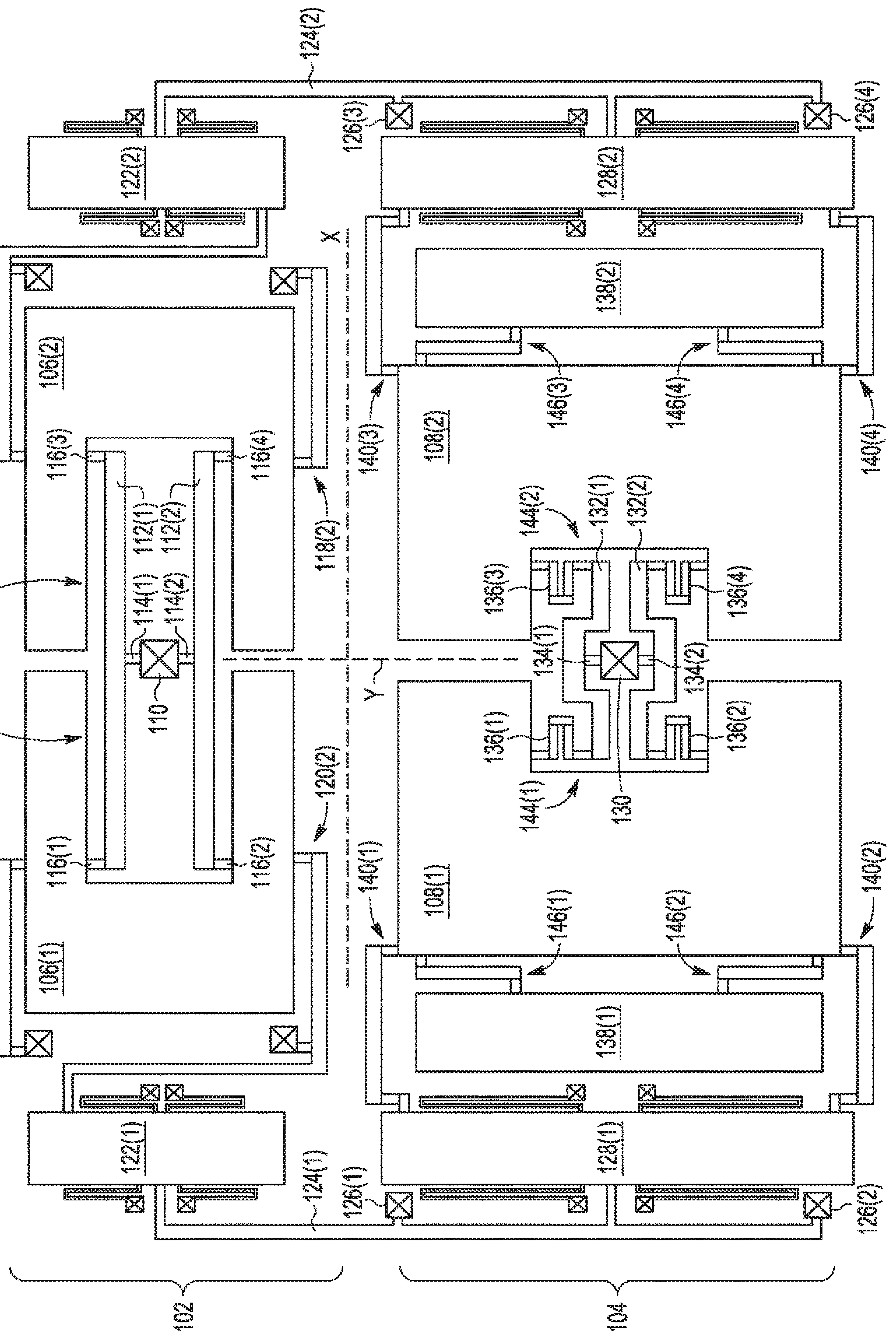
Primary Examiner — John E Chapman, Jr.

(57) **ABSTRACT**

A microelectromechanical system (MEMS) gyroscope device includes a substrate having a surface parallel to a plane; first and second proof masses driven to slide back and forth past one another in a first directional axis of the plane, where the first and second proof masses respectively have a first and second recess in a respective side closest to the other proof mass; a pivot structure coupled to the first proof mass within the first recess and to the second proof mass within the second recess; an anchor between the first and second recesses and coupled to a mid-point of the pivot structure; and third and fourth proof masses driven to move toward and away from one another in a second directional axis of the plane that is perpendicular to the first directional axis; where the proof masses move in response to angular velocity in one or more directional axes.

15 Claims, 11 Drawing Sheets

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X
Y

FIG. 1

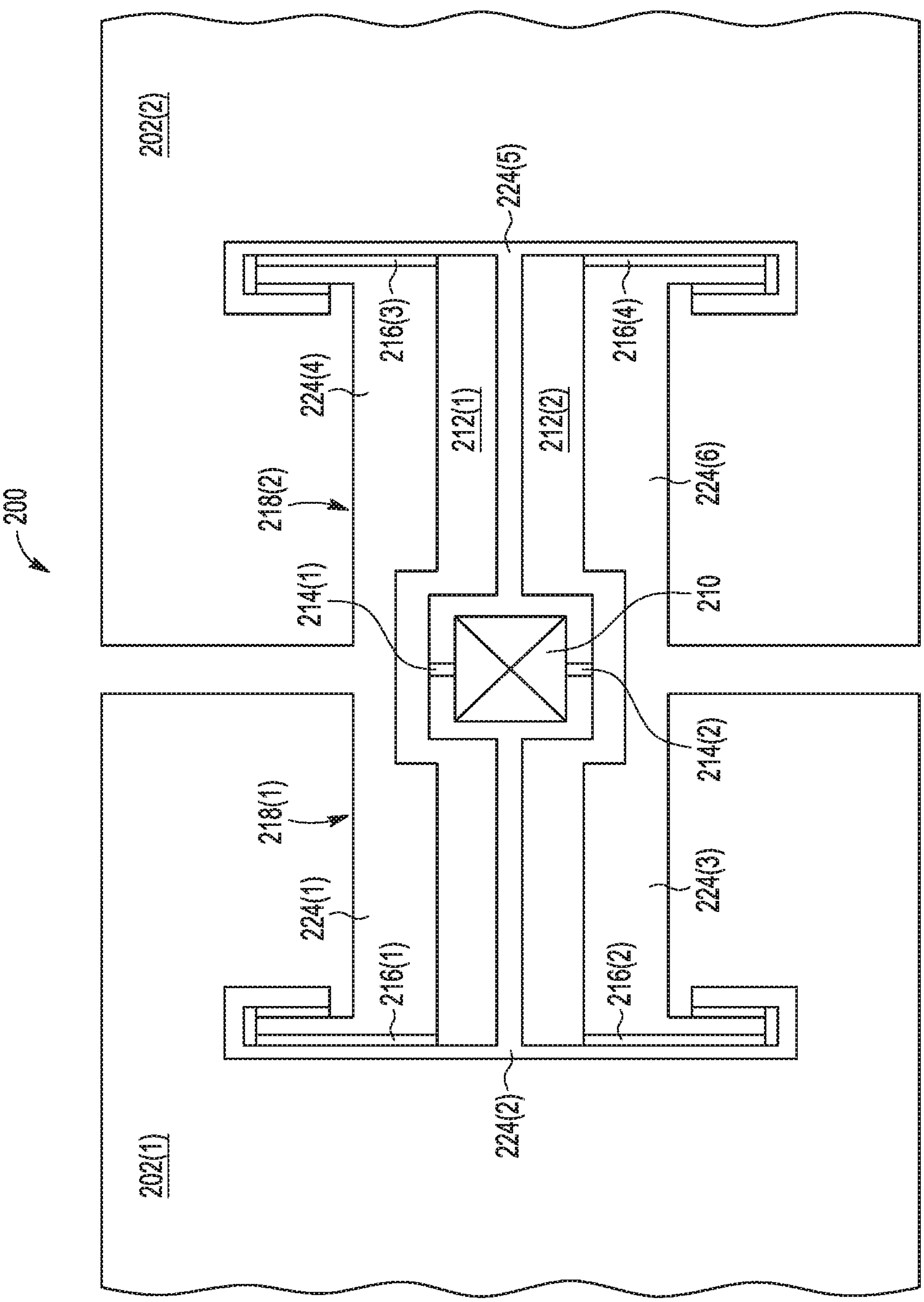
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FIG. 2

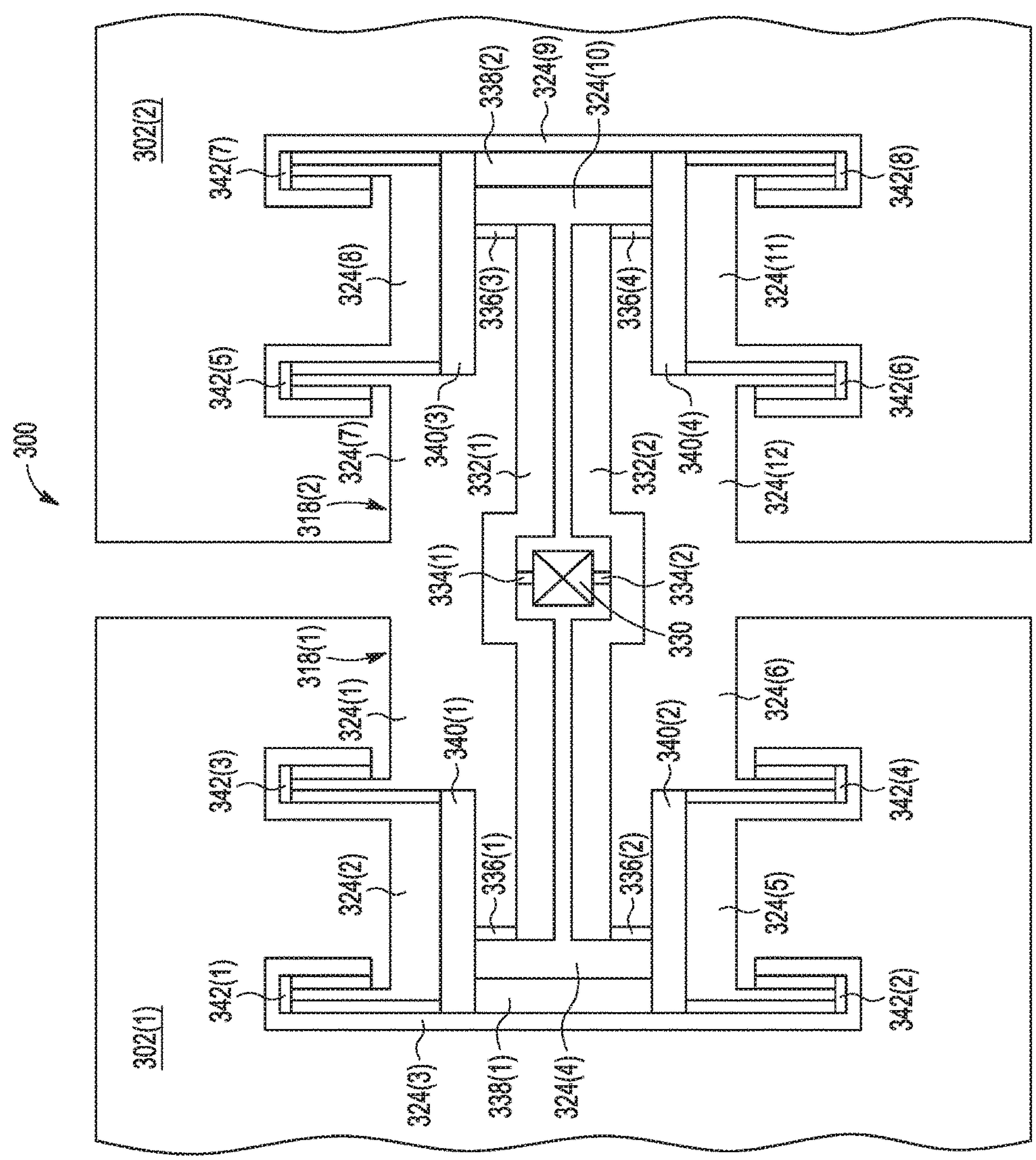
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FIG. 3

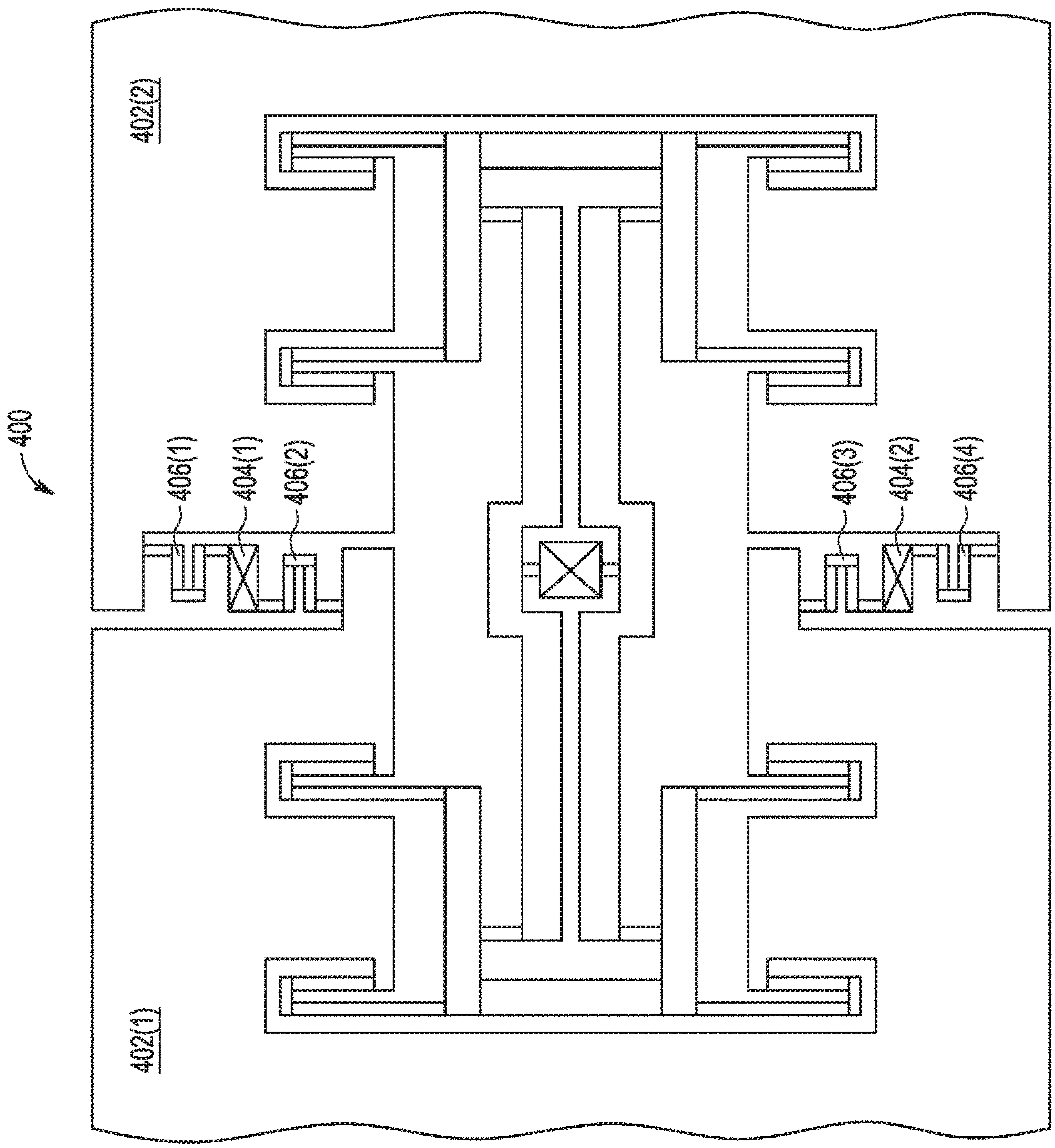
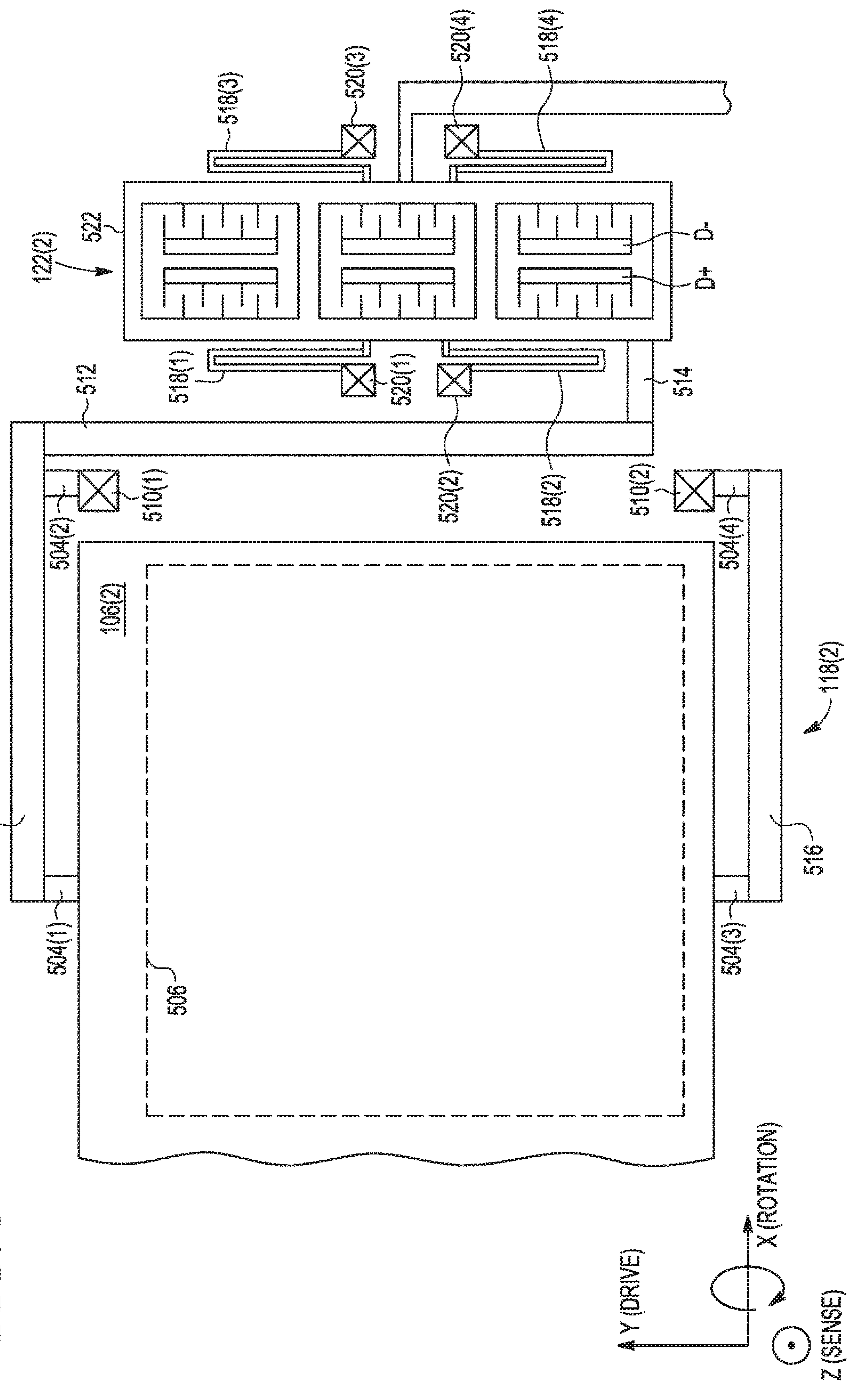


FIG. 4



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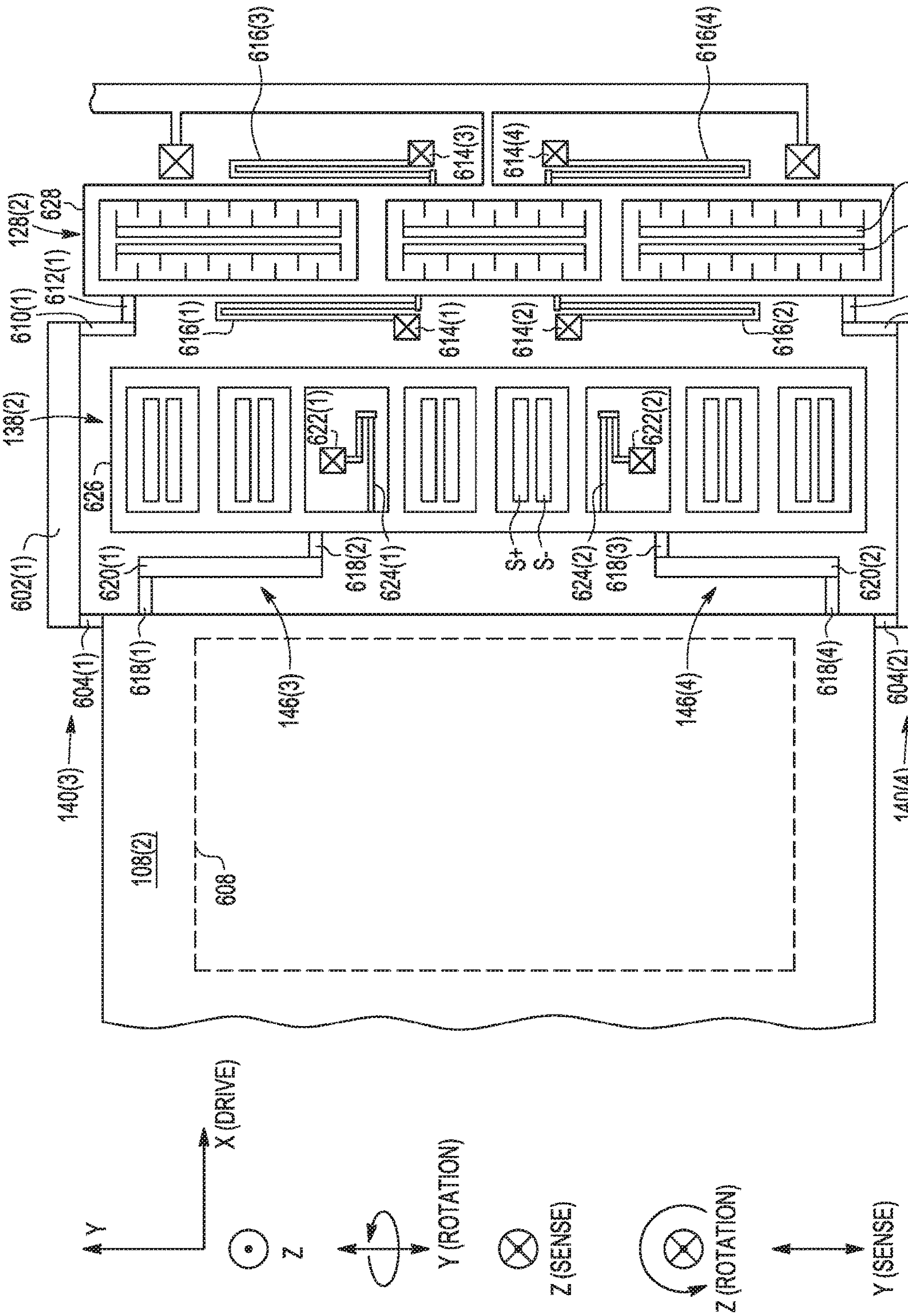
X (ROTATION)
Z (SENSE)

FIG. 5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Y (SENSE)

FIG. 6

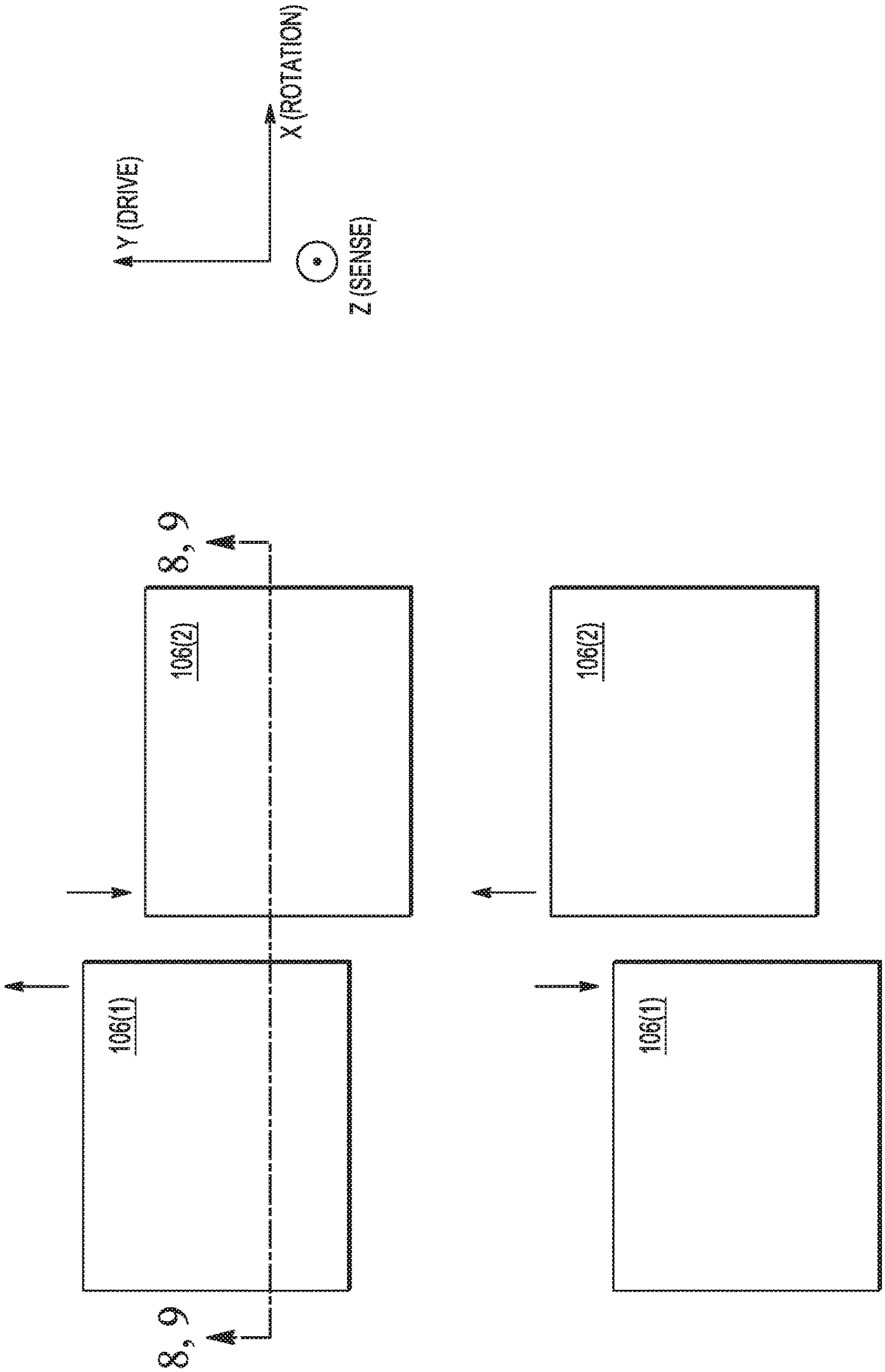
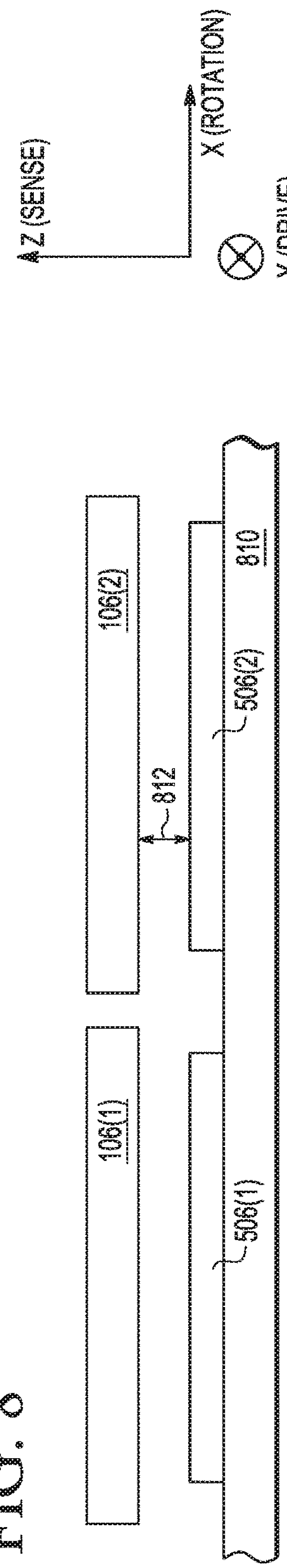


FIG. 7

FIG. 8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506(1)
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FIG. 9

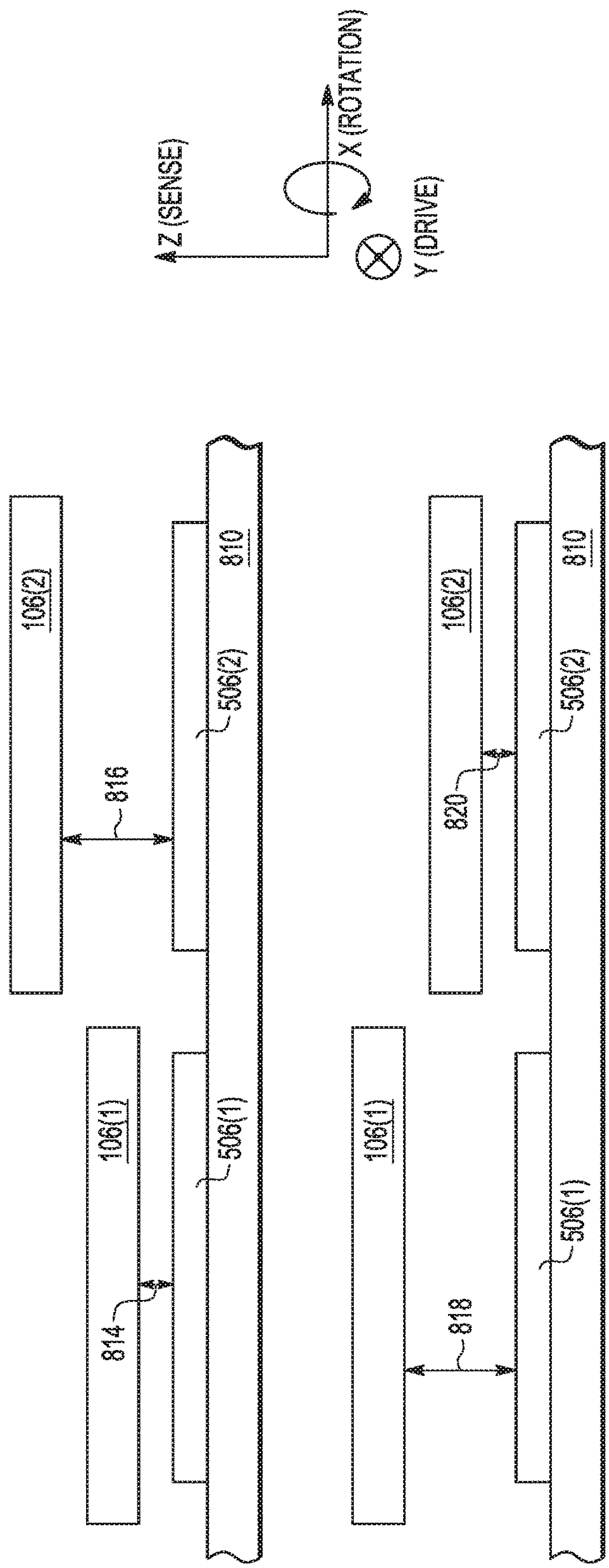
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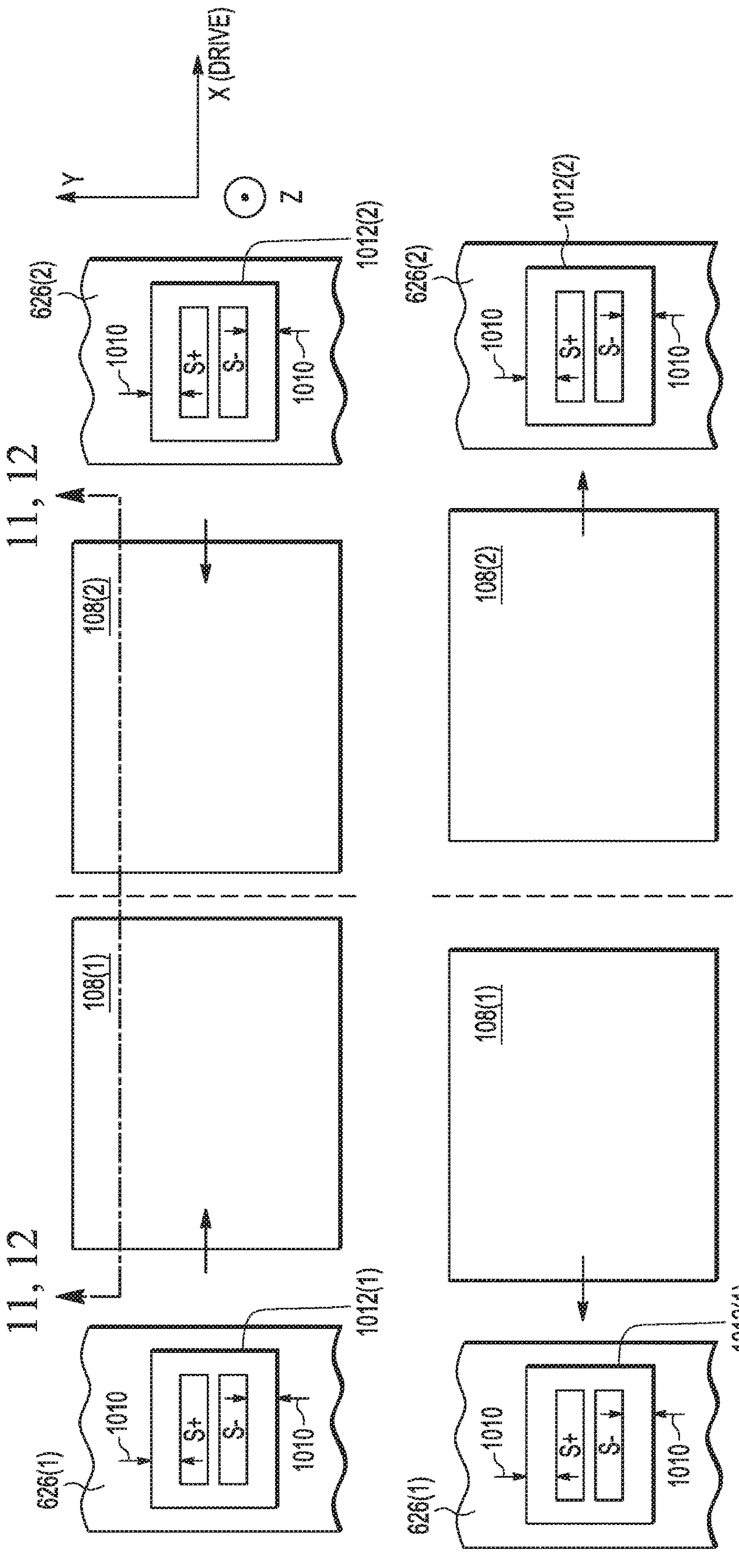
FIG. 10



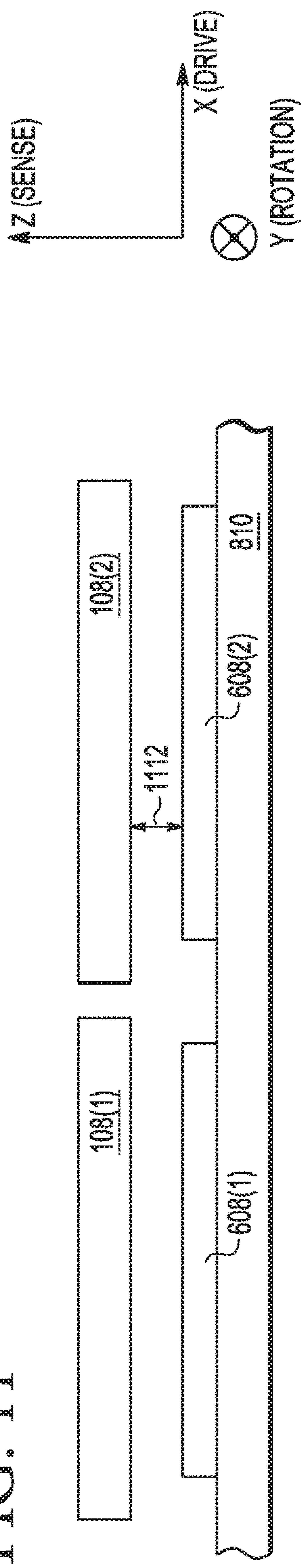

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FIG. 11

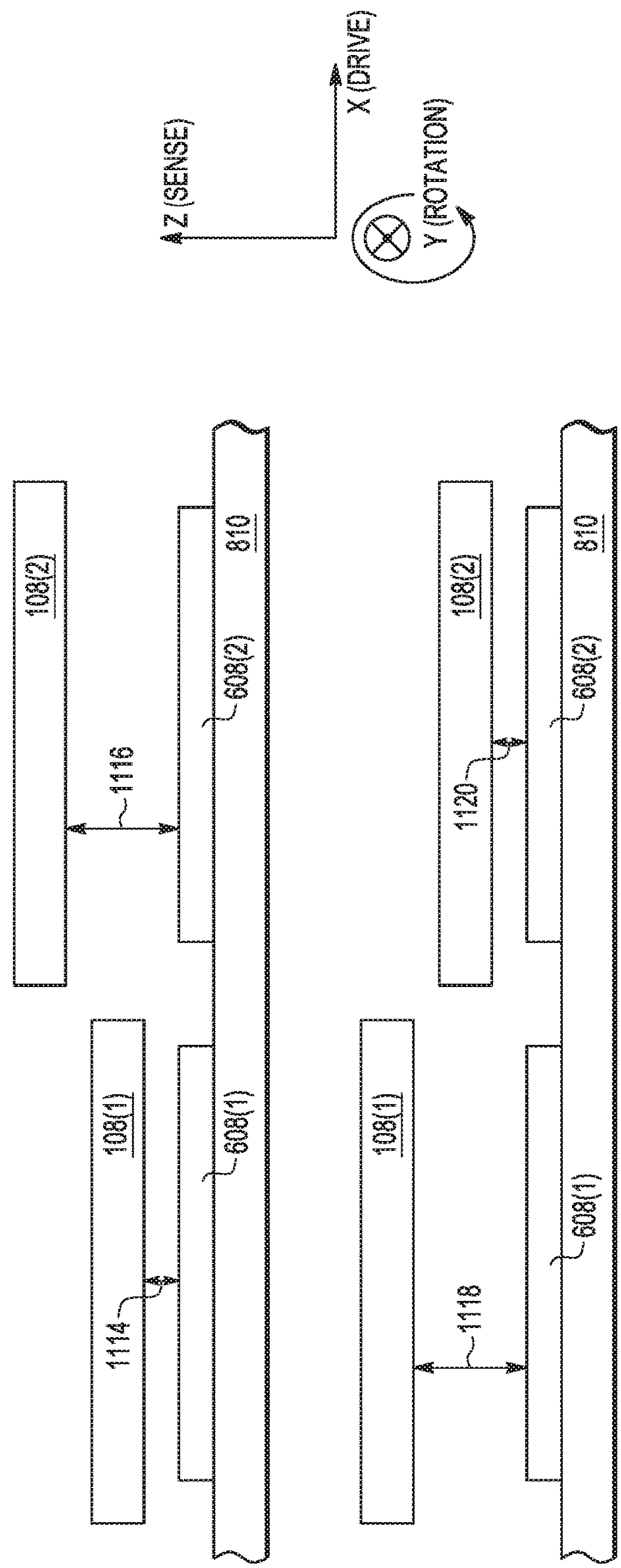
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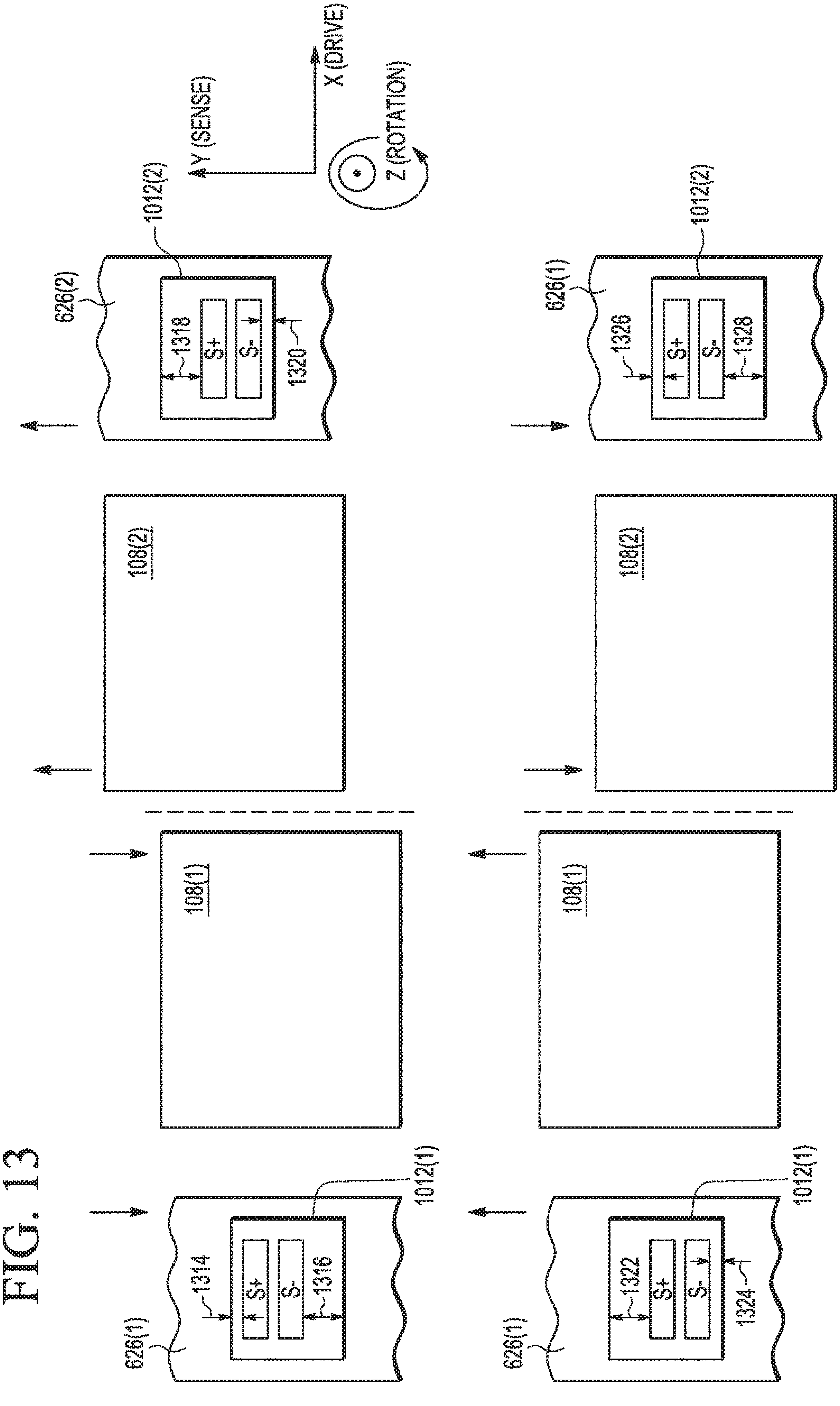
FIG. 12

FIG. 13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1324

MEMS GYROSCOPE DEVICE

BACKGROUND

Field

This disclosure relates generally to microelectromechanical systems (MEMS), and more specifically, to a MEMS device having a drive structure movable in three axes.

Related Art

Microelectromechanical systems (MEMS) devices are widely used in applications such as automotive, inertial guidance systems, household appliances, protection systems for a variety of devices, and many other industrial, scientific, and engineering systems. Such MEMS devices maybe used to sense a physical condition such as acceleration, angular velocity, pressure, or temperature, and to provide an electrical signal representative of the sensed physical condition. MEMS sensor designs are highly desirable for operation in high gravity environments and in miniaturized devices, and due to their relatively low cost.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be better understood, and its numerous objects, features, and advantages made apparent to those skilled in the art by referencing the accompanying drawings.

FIG. **1** illustrates a block diagram depicting a top-down view of an example MEMS device in which the disclosure is implemented, according to some embodiments.

FIGS. **2** and **3** illustrate block diagrams depicting top-down views of example pivot structures of a MEMS device in which the disclosure is implemented, according to some embodiments.

FIG. **4** illustrates a block diagram depicting a top-down view of example common mode drive spring structures of a MEMS device in which the disclosure is implemented, according to some embodiments.

FIGS. **5** and **6** illustrate block diagrams depicting top-down views of example components of a MEMS device in which the disclosure is implemented, according to some embodiments.

FIGS. **7**, **10**, and **13** illustrate block diagrams depicting top-down views of example proof mass movement in a MEMS device in which the disclosure is implemented, according to some embodiments.

FIGS. **8**, **9**, **11**, and **12** illustrate block diagrams depicting cross-sectional views of example proof mass movement in a MEMS device in which the present disclosure is implemented, according to some embodiments.

The present invention is illustrated by way of example and is not limited by the accompanying figures, in which like references indicate similar elements, unless otherwise noted. Elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale.

DETAILED DESCRIPTION

The following sets forth a detailed description of various embodiments intended to be illustrative of the invention and should not be taken to be limiting.

Overview

One particular type of microelectromechanical systems (MEMS) device that is used in a variety of applications is a gyroscope. Typically, a MEMS gyroscope includes (among other component parts) one or more movable elements, also referred to as proof masses. In an example MEMS device, a proof mass is resiliently suspended above a substrate by one or more compliant torsion springs and is driven by a frequency to vibrate in a given direction, referred to herein as the drive direction. When the proof mass experiences angular velocity, or rotation about an axis (also referred to herein as the rotation direction), that is perpendicular to the drive direction, the torsion springs enable movement of the proof mass in a sense direction that is orthogonal to the drive direction and the rotation direction. Generally, electrodes are placed to detect the movement of the proof mass in the orthogonal sense direction. For example, as the proof mass moves closer or farther away from an electrode, the capacitance between the proof mass and the electrode changes, which is measured and may then be converted into an electrical signal having a parameter magnitude (e.g., voltage, current, frequency, etc.) that is proportional to the movement in the rotation direction.

The present disclosure provides embodiments of a MEMS gyroscope device that is movable in three axes to measure angular velocity in three axes. The present disclosure provides for two pairs of proof masses that are parallel to a plane of a surface of an underlying substrate (e.g., the two pairs of proof masses lie in-plane). The first pair of proof masses are driven to slide back and forth past one another in a first in-plane directional axis (e.g., in the Y-directional axis), while the second pair of proof masses are driven to move toward and away from one another (e.g., tuning fork vibration) in a second in-plane directional axis (e.g., in the X-directional axis) perpendicular to the first in-plane directional axis. It is noted that the drive motion of each proof mass relative to one another in a given pair is in anti-phase, or in opposing directions from one another (e.g., one proof mass of the pair moves in a positive direction of a directional axis, while the other proof mass of the pair moves in a negative direction of the directional axis).

As the first pair of proof masses experience angular velocity in the second in-plane directional axis, the first pair of proof masses move in an out-of-plane directional axis (e.g., in the Z-directional axis) that is orthogonal to the first and second in-plane directional axes. As the second pair of proof masses experience angular velocity in the first in-plane directional axis, the second pair of proof masses move in the out-of-plane directional axis. As the second pair of proof masses experience angular velocity in the out-of-plane directional axis, the second pair of proof masses move in the first in-plane directional axis.

In some embodiments, the present disclosure also provides for structures to reduce or suppress common mode drive motion, including pivot structures and several four bar linkages, as further discussed below. These structures improve the sense efficiency of the MEMS gyroscope device, where the structures maintain a substantially parallel orientation of a proof mass to an underlying electrode. In some embodiments, the present disclosure also provides for linking bars that couple the in-plane drive motion of the first pair of proof masses with the in-plane drive motion of the second pair of proof masses. In some embodiments, the present disclosure also provides that in-plane drive motions of the proof masses have a single drive frequency. In this manner, the present disclosure provides embodiments of a MEMS gyroscope device that has a compact design due in part to the drive motion of the pairs of proof masses being in perpendicular in-plane directions and the sense motion of the pair of proof masses for two axes in an orthogonal out-of-plane direction.

EXAMPLE EMBODIMENTS

FIG. **1** illustrates a block diagram depicting a top-down view of an example MEMS device **100** including a gyroscope (also referred to as a MEMS gyroscope device **100**) in which the disclosure is implemented. In the embodiment shown, MEMS device **100** includes two pairs of proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**), actuators **122**(**1**)-(**2**) and **128**(**1**)-(**2**), sense structures **138**(**1**)-(**2**), and various structures including torsion springs (also referred to as springs), bars (which may be straight bars or bent bars like an L-shaped or 90° bent bar, a 45° bent bar, or bars bent at other degree angles), and anchors, as further discussed below. MEMS device **100** also includes sense electrodes, which are further discussed in connection with FIG. **5-13**. Other embodiments of a MEMS gyroscope device may also include different or additional embodiments of structures, such as pivot structures and common mode drive spring structures, which are further discussed in connection with FIG. **2-4**. Additional or fewer components may be present in other embodiments.

The components of a MEMS device, like the embodiment shown in FIG. **1**, are formed on and over a surface of a substrate (e.g., shown as **810** in FIG. **8**). The substrate may be implemented as a semiconductor substrate, which can be any semiconductor material or combinations of materials, such as gallium arsenide, silicon germanium, silicon-on-insulator (SOI), silicon, monocrystalline silicon, the like, and combinations of the above. The components of a MEMS device, like the embodiment shown in FIG. **1**, may be produced by utilizing current and upcoming micromachining techniques of depositing, patterning, etching, and the like. It is noted that while the components of a MEMS gyroscope device discussed herein may be illustrated as separate components, it should be understood that such components may be formed from a single block of semiconductor material (which may be formed by one or more layers of semiconductor material) and do not necessarily have physical borders or boundaries delimiting one component from another at an illustrated connection point or junction. One component that is "attached" to another component may also be referred to as being "connected" or "joined" to another component at the illustrated connection point or junction. It should be further understood that the use of relational terms, if any, such as first and second, top and bottom, and the like are used to distinguish one from another entity or action without necessarily requiring or implying any actual such relationship or order between such entities or actions.

The substrate surface is parallel to an X-Y plane having an X-directional axis and a perpendicular Y-directional axis. It is noted that "in-plane" movement refers to movement relative to the X- and Y-directional axes, while "out-of-plane" movement refers to movement relative to a Z-directional axis that is normal to the x-y plane. The X-Y plane is parallel to the page of FIG. **1**, while the Z-directional axis is normal to the page of FIG. **1**.

In some embodiments, proof masses may also have openings or holes formed through them (e.g., in an out-of-plane direction) to ensure that an etchant reaches one or more sacrificial layers under the proof masses during production of a MEMS device like that shown in FIG. **1**, where the etchant removes the sacrificial layer(s) and structurally releases the components of the MEMS device.

Proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**) are each positioned in space above the surface of the substrate and are each parallel to the X-Y plane. Proof mass **106**(**1**) is laterally adjacent to proof mass **106**(**2**) in the X-Y plane, and proof mass **108**(**1**) is laterally adjacent to proof mass **108**(**2**) in the X-Y plane. It is noted that "laterally adjacent" proof masses indicates that the two proof masses are next to one another without an intervening proof mass between them. In some embodiments, proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**) lie in a common plane that is parallel to the substrate surface (as well as to the X-Y plane discussed above).

In the embodiment shown in FIG. **1**, the pair of proof masses **106**(**1**)-(**2**) are also laterally adjacent to the pair of proof masses **108**(**1**)-(**2**) in the X-Y plane. For example, each proof mass is illustrated as being in a respective quadrant of the X-Y plane, where proof masses **106**(**1**) and **108**(**1**) are laterally adjacent to one another, and proof masses **106**(**2**) and **108**(**2**) are laterally adjacent to one another. Put another way, as viewed from a top-down view like that shown in FIG. **1**, each proof mass has a side closest to its paired proof mass and a perpendicular side closest to one of the other pair of proof masses. For example, proof mass **106**(**1**) has a first side closest to its paired proof mass **106**(**2**) (shown as a side parallel to the positive Y-directional axis) and a second side closest to proof mass **108**(**1**) (shown as a side parallel to the negative X-directional axis), where the second side is perpendicular to the first side. Similarly, proof mass **108**(**2**) has a first side closest to its paired proof mass **108**(**1**) (shown as a side parallel to the negative Y-directional axis) and a second side closest to proof mass **106**(**2**) (shown as a side parallel to the positive X-directional axis), where the second side is perpendicular to the first side.

Proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**) are known quantities of mass that are used to detect angular velocity, or rotation about an axis, in one or more directional axes. In the embodiment shown in FIG. **1**, proof masses **106**(**1**)-(**2**) detect angular velocity in the X-directional axis (which is further discussed below in connection with FIG. **7-9**), while proof masses **108**(**1**)-(**2**) detect angular velocity in the Y- and Z-directional axes (which is further discussed below in connection with FIG. **10-13**). In other embodiments, proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**) may detect angular velocity in different directional axes, such as where proof masses **106**(**1**)-(**2**) detect angular velocity in the X- and Z-directional axes, while proof masses **108**(**1**)-(**2**) detect angular velocity in the Y-directional axis. Other embodiments may include either proof masses **106**(**1**)-(**2**) or proof masses **108**(**1**)-(**2**) independently operating as a sensor to detect angular velocity about a single X-, Y-, or Z-directional axis.

Proof mass **106**(**1**) includes recess **142**(**1**) in the side closest to its paired proof mass **106**(**2**), and proof mass **106**(**2**) includes recess **142**(**2**) in the side closest to its paired proof mass **106**(**1**). Proof mass **108**(**1**) includes recess **144** (**1**) in the side closest to its paired proof mass **108**(**2**), and proof mass **108**(**2**) includes recess **144**(**2**) in the side closest to its paired proof mass **108**(**1**). As referred to herein, a recess (such as recesses **142**(**1**)-(**2**) and **144**(**1**)-(**2**)) is a cavity or void or indention or a volume of space located on an edge of the proof mass' outer perimeter that is parallel to the X-Y plane (where the outer perimeter includes the outer sidewalls of the proof mass, as viewed from the top-down view in FIG. **1**), within which the proof mass is absent. A recess extends through the proof mass to the top and bottom surfaces of the proof mass that are parallel to the X-Y plane, and includes at least three sidewalls. Various structures are also formed within a recess by a number of openings through the proof mass, where the structures attach to sidewalls of the recess. It is also noted that recesses **142**(**1**)-(**2**), as well as any structure formed within or between the recesses **142**(**1**)-(**2**), like a pivot structure or an anchor, are formed by a number of openings in and through proof masses **106**(**1**)-(**2**). Similarly, recesses **144**(**1**)-(**2**), as well as any structure formed within or between the recesses **144**(**1**)-(**2**), are formed by a number of openings in and through proof masses **108**(**1**)-(**2**). Such openings are further discussed below in connection with FIGS. **2** and **3**.

Anchor **110** is formed on the substrate and located between recesses **142**(**1**) and **142**(**2**). Pivot bar **112**(**1**) is coupled to anchor **110** by spring **114**(**1**). One end of pivot bar **112**(**1**) is coupled to a sidewall of recess **142**(**1**) by spring **116**(**1**), and the opposing end of pivot bar **112**(**1**) is coupled to a sidewall of recess **142**(**2**) by spring **116**(**3**). Pivot bar **112**(**2**) is coupled to anchor **110** by spring **114**(**2**). One end of pivot bar **112**(**2**) is coupled to a sidewall of recess **142**(**1**) by spring **116**(**2**), and the opposing end of pivot bar **112**(**2**) is coupled to a sidewall of recess **142**(**2**) by spring **116**(**4**). While pivot bars **112**(**1**)-(**2**) are shown as straight bars, other shaped bars may be used, such as bars that are bent around anchor **110** by some angle (e.g., like bars **132**(**1**)-(**2**) further discussed below). Also, while springs **116**(**1**)-(**4**) are shown as straight springs, other shaped springs may be used, such as U-shaped springs (e.g., like springs **136**(**1**)-(**4**) further discussed below) or J-shaped springs (e.g., like springs **216**(**1**)-(**4**), further discussed below in connection with FIG. **2**).

Pivot bars **112**(**1**)-(**2**), springs **114**(**1**)-(**2**), and springs **116**(**1**)-(**4**) form a pivot structure for proof masses **106**(**1**)-(**2**), where the pivot structure moves flexibly about anchor **110** in the Y-directional axis for drive motion (further discussed below in connection with FIGS. **5** and **7**), and in the Z-directional axis for sense motion (further discussed below in connection with **8** and **9**). Proof masses **106**(**1**) and **106**(**2**) and their respectively attached ends of pivot bars **112**(**1**) and **112**(**2**) move in anti-phase, which is to say they move in opposite directions during drive and sense motion. For example, as proof mass **106**(**1**) moves in one direction of the Y-directional axis (e.g., positive direction), proof mass **106**(**2**) moves in an opposite direction in the Y-directional axis (e.g., negative direction). In other words, proof mass **106**(**1**) and proof mass **106**(**2**) slide back and forth past one another in the Y-directional axis. Similarly, as proof mass **106**(**1**) moves in one direction of the Z-directional axis (e.g., negative direction), proof mass **106**(**2**) moves in an opposite direction of the Z-directional axis (e.g., positive direction). The pivot structure ensures that proof masses **106**(**1**)-(**2**) have sense motion in the Z-directional axis that is substantially parallel to sense electrodes underlying the proof masses **106**(**1**)-(**2**), making the sense area where the proof masses **106**(**1**)-(**2**) overlie the sense electrodes more efficient.

An anchor structure **118**(**1**) is coupled to an outer wall of proof mass **106**(**1**), and one end of a linking structure **120**(**2**) is coupled to an opposing outer wall of proof mass **106**(**1**). An anchor structure **118**(**2**) is coupled to an outer wall of proof mass **106**(**2**) and one end of a linking structure **120**(**1**) is coupled to an opposing outer wall of proof mass **106**(**2**). An opposing end of linking structure **120**(**2**) is coupled to actuator **122**(**1**), and an opposing end of linking structure **120**(**1**) is coupled to actuator **122**(**2**). In the embodiment shown, connection points of the structures **118**(**1**) and **120**(**2**) to the proof mass are aligned with connection points of the pivot structure to form a single axis (e.g., springs of the structures **118**(**1**) and **120**(**2**) are aligned with springs **116**(**2**) and **116**(**2**)). In other embodiments, the connection points are not aligned. Actuators **122**(**1**)-(**2**) and structures **118**(**1**)-(**2**) and **120**(**1**)-(**2**) are further discussed below in connection with FIG. **5**.

Actuator **128**(**1**) is coupled to proof mass **108**(**1**) by a linking structure **140**(**1**) on one outer wall and by a linking structure **140**(**2**) on an opposing outer wall of proof mass **108**(**1**). Actuator **128**(**2**) is coupled to proof mass **108**(**2**) by a linking structure **140**(**3**) on one outer wall and by a linking structure **140**(**4**) on an opposing outer wall of proof mass **108**(**2**). In the embodiment shown, connection points of the structures **140**(**1**) and **140**(**2**) to proof mass **108**(**1**) are aligned with one another (e.g., springs of the structures **140**(**1**) and **140**(**2**) are aligned), and connection points of the structures **140**(**3**) and **140**(**4**) are aligned with one another. Actuators **128**(**1**)-(**2**) and structures **140**(**1**)-(**4**) are further discussed below in connection with FIG. **6**.

In the embodiment shown, actuator **122**(**1**) is coupled to actuator **128**(**1**) by a drive motion linking structure **124**(**1**), and actuator **122**(**2**) is coupled to actuator **128**(**2**) by another drive motion linking structure **124**(**2**). Drive motion linking structure **124**(**1**) is also coupled to anchors **126**(**1**) and **126**(**2**) formed on the substrate, and drive motion linking structure **124**(**2**) is coupled to anchors **126**(**3**) and **126**(**4**) formed on the substrate. Drive motion linking structure **124**(**1**) is configured to couple the drive motion provided by actuators **122**(**1**) and **128**(**1**), and drive motion linking structure **124**(**2**) is configured to couple the drive motion provided by actuators **122**(**2**) and **128**(**2**). It is noted that drive motion linking structures **124**(**1**)-(**2**) are used in embodiments where it is desirable to achieve a single drive frequency for proof masses **106**(**1**)-(**2**) and **108**(**1**)-(**2**).

Anchor **130** is formed on the substrate and located between recesses **144**(**1**) and **144**(**2**) of proof masses **108**(**1**)-(**2**). Pivot bar **132**(**1**) is coupled to anchor **130** by spring **134**(**1**). One end of pivot bar **132**(**1**) is coupled to a sidewall of recess **144**(**1**) by spring **136**(**1**), and the opposing end of pivot bar **132**(**1**) is coupled to a sidewall of recess **144**(**2**) by spring **136**(**3**). Pivot bar **132**(**2**) is coupled to anchor **130** by spring **134**(**2**). One end of pivot bar **132**(**2**) is coupled to a sidewall of recess **144**(**1**) by spring **136**(**2**), and the opposing end of pivot bar **132**(**2**) is coupled to a sidewall of recess **144**(**2**) by spring **136**(**4**). While pivot bars **132**(**1**)-(**2**) are shown as bars bent around anchor **130**, other shaped bars may be used, such as straight bars (e.g., like bars **112**(**1**)-(**2**) discussed above). Also, while springs **136**(**1**)-(**4**) are shown as U-shaped springs, other shaped springs may be used, such as straight springs (e.g., like springs **116**(**1**)-(**4**) discussed above) or J-shaped springs (e.g., like springs **216**(**1**)-(**4**), further discussed below in connection with FIG. **2**).

Pivot bars **132**(**1**)-(**2**), springs **134**(**1**)-(**2**), and springs **136**(**1**)-(**4**) form a pivot structure for proof masses **108**(**1**)-(**2**), where the pivot structure moves flexibly about anchor **130** in the Y-directional axis for sense motion (further discussed below in connection with FIG. **13**), and in the Z-directional axis for sense motion (further discussed below in connection with **11** and **12**). Proof masses **108**(**1**)-(**2**) are also able to move flexibly toward and away (e.g., tuning fork motion) from the anchor **130** in the X-directional axis for drive motion (further discussed below in connection with FIG. **10**). Proof masses **108**(**1**) and **108**(**2**) and their respectively attached ends of pivot bars **132**(**1**) and **132**(**2**) move in anti-phase, which is to say they move in opposite directions during drive and sense motion. For example, as proof mass **108**(**1**) moves in one direction of the Y-directional axis (e.g. positive direction), proof mass **108**(**2**) moves in an opposite direction of the Y-directional axis (e.g., negative direction). Similarly, as proof mass **108(1)** moves in one direction of the Z-directional axis (e.g., negative direction), proof mass **108(2)** moves in an opposite direction of the Z-directional axis (e.g., positive direction). The pivot structure ensures that proof masses **108(1)-(2)** have sense motion in the Z-directional axis that is substantially parallel to sense electrodes underlying the proof masses **108(1)-(2)**, making the sense area where the proof masses **108(1)-(2)** overlie the sense electrodes more efficient.

Proof mass **108(1)** is also coupled to a sense structure **138(1)** by isolating structures **146(1)-(2)**, and proof mass **108(2)** is coupled to sense structure **138(2)** by isolating structures **146(3)-(4)**. Each sense structure **138(1)-(2)** includes a number of sense electrodes that detect motion in the Y-directional axis. Sense structures **138(1)-(2)** and isolating structures **146(1)-(4)** are further discussed below in connection with FIG. **6**.

FIG. **2** illustrates a block diagram depicting a top-down view of an example pivot structure **200** of a MEMS device in which the disclosure is implemented. In other embodiments, pivot structure **200** may be used instead of the pivot structure illustrated in FIG. **1** between proof masses **106(1)** and **106(2)**, or may be used instead of the pivot structure illustrated in FIG. **1** between proof masses **108(1)** and **108(2)**.

Anchor **210** is formed on the substrate and located between recesses **218(1)** and **218(2)** of proof masses **202(1)-(2)**. Pivot bar **212(1)** is coupled to anchor **210** by spring **214(1)**. One end of pivot bar **212(1)** is coupled to a sidewall of recess **218(1)** by spring **216(1)**, and the opposing end of pivot bar **212(1)** is coupled to a sidewall of recess **218(2)** by spring **216(3)**. Pivot bar **212(2)** is coupled to anchor **210** by spring **214(2)**. One end of pivot bar **212(2)** is coupled to a sidewall of recess **218(1)** by spring **216(2)**, and the opposing end of pivot bar **212(2)** is coupled to a sidewall of recess **218(2)** by spring **216(4)**. Pivot bars **212(1)-(2)**, springs **214(1)-(2)**, and springs **216(1)-(4)** form pivot structure **200**, where the pivot structure **200** moves flexibly about anchor **210** in the Y- and Z-directional axes, and proof masses **202(1)-(2)** are also able to move flexibly toward and away from the anchor **210** in the X-directional axis, making pivot structure **200** suitable for use as a pivot structure for both proof masses **106(1)-(2)** and **108(1)-(2)**.

It is also noted that recesses **218(1)-(2)**, as well as pivot structure **200** within the recesses **218(1)-(2)** and anchor **210** between the recesses **218(1)-(2)**, are formed by openings **224(1)-(6)** in and through proof masses **202(1)-(2)**. Additional or fewer openings may be used to form the structures within the recesses in other embodiments. Each opening **224** forms one or more sidewalls of the respective recess **218**. In the embodiment shown, recesses **218(1)-(2)** have more than 3 sidewalls. For example, additional sidewalls of recess **218(1)** are formed around spring **216(1)** where a portion of proof mass **202(1)** has been further removed (as compared with recess **142(1)**, for example). Springs **216(1)-(4)** each attach to a respective one of proof masses **202(1)-(2)** at a sidewall of the respective recess **218(1)-(2)**.

FIG. **3** illustrates a block diagram depicting a top-down view of another example pivot structure **300** of a MEMS device in which the disclosure is implemented. In other embodiments, pivot structure **300** may be used instead of the pivot structure illustrated in FIG. **1** between proof masses **106(1)** and **106(2)**, or may be used instead of the pivot structure illustrated in FIG. **1** between proof masses **108(1)** and **108(2)**.

Anchor **330** is formed on the substrate and located between recesses **318(1)** and **318(2)** of proof masses **302(1)-(2)**. Pivot bar **332(1)** is coupled to anchor **330** by spring **334(1)**. Pivot bar **332(2)** is coupled to anchor **330** by spring **334(2)**. The ends of pivot bars **332(1)-(2)** are coupled to interior sidewalls of a respective C-shaped linking structure, one such structure formed by horizontal bars **340(1)-(2)** and vertical bar **338(1)**, and another formed by horizontal bars **340(3)-(4)** and vertical bar **338(2)**, where "horizontal" bars and "vertical" bars are used as positional terms with respect to the layout of FIG. **3**. In other words, horizontal bars are oriented in the horizontal direction of FIG. **3**, and vertical bars are oriented in the vertical direction of FIG. **3**. It is also noted that the C-shaped linking structures need not have a physical boundary at the junction of horizontal and vertical bars, since the horizontal and vertical bars may be formed from a single block of semiconductor material. One end of pivot bar **332(1)** is coupled to a sidewall of bar **340(1)** by spring **336(1)**, and the opposing end of pivot bar **332(1)** is coupled to a sidewall of bar **340(3)** by spring **336(3)**. One end of pivot bar **332(2)** is coupled to a sidewall of bar **340(2)** by spring **336(2)**, and the opposing end of pivot bar **332(2)** is coupled to a sidewall of bar **340(4)** by spring **336(4)**.

Each C-shaped linking structure is coupled to sidewalls of the respective recess **318(1)-(2)** by a number of springs **342**. In the embodiment shown, bar **340(1)** is coupled to sidewalls of recess **318(1)** by springs **342(1)** and **342(3)**, and bar **340(2)** is coupled to sidewalls of recess **318(1)** by springs **342(2)** and **342(4)**. Bar **340(3)** is coupled to sidewalls of recess **318(2)** by springs **342(5)** and **342(7)**, and bar **340(4)** is coupled to sidewalls of recess **318(2)** by springs **342(6)** and **342(8)**.

Pivot bars **332(1)-(2)**, springs **334(1)-(2)**, springs **336(1)-(4)**, bars **340(1)-(4)**, bars **338(1)-(2)**, and springs **342(1)-(8)** form pivot structure **300**, where the pivot structure **300** moves flexibly about anchor **330** in the Y- and Z-directional axes, and proof masses **302(1)-(2)** are also able to move flexibly toward and away from the anchor **210** in the X-directional axis, making pivot structure **300** suitable for use as a pivot structure for both proof masses **106(1)-(2)** and **108(1)-(2)**.

It is also noted that recesses **318(1)-(2)**, as well as pivot structure **300** within the recesses **318(1)-(2)** and anchor **330** between the recesses **318(1)-(2)**, are formed by openings **324(1)-(12)** in and through proof masses **302(1)-(2)**. Additional or fewer openings may be used to form the structures within the recesses in other embodiments. Each opening **324** forms one or more sidewalls of the respective recess **318**. In the embodiment shown, recesses **318(1)-(2)** have more than 3 sidewalls. For example, additional sidewalls of recess **318(1)** are formed around springs **342(1)** and **342(3)** where a portion of proof mass **302(1)** has been further removed (as compared with recess **136(1)**, for example). Springs **342(1)-(8)** each attach to a respective one of proof masses **302(1)-(2)** at a sidewall of the respective recess **318(1)-(2)**.

FIG. **4** illustrates a block diagram depicting a top-down view of a pair of example common mode drive spring structures **400** of a MEMS device in which the disclosure is implemented. Common mode drive spring structures **400** are located between a pair of proof masses **402(1)-(2)** on either side of a pivot structure between the pair of proof masses **402(1)-(2)**. Common mode drive spring structures **400** are configured to suppress or minimize common mode drive motion in order to improve efficiency of movement of the proof masses **402(1)-(2)**. In combination with the pivot structure (like that shown in FIG. **1**, **2**, or **3**) between proof masses **108(1)-(2)** of FIG. **1**, the common mode drive spring structures **400** ensure that proof masses **108**(**1**)-(**2**) have sense motion in the Z-directional axis that is substantially parallel to underlying sense electrodes, making the sense area where the proof masses **108**(**1**)-(**2**) overlap the sense electrodes more efficient. The common mode drive spring structures **400** also ensures that proof masses **402**(**1**)-(**2**) undergo a drive motion where the proof masses move toward and away from each other. Spring structures **406**(**1**)-(**2**) are configured such that it has a low resistance to this tuning fork drive motion, whereas when proof masses **402** (**1**)-(**2**) undergo motions in the same direction (as common mode motion), the structure **400** in cooperation with anchor **404** and spring structures **406** will introduce a large stiffness or resistance.

One common mode drive spring structure **400** includes anchor **404**(**1**) formed on the substrate, spring **406**(**1**) having one end attached to the proof mass **402**(**2**) and an opposing end attached to anchor **404**(**1**), and spring **406**(**2**) having one end attached to the proof mass **402**(**1**) and an opposing end attached to anchor **404**(**1**). Another common mode drive spring structure **400** includes anchor **404**(**2**) formed on the substrate, spring **406**(**3**) having one end attached to the proof mass **402**(**1**) and an opposing end attached to anchor **404**(**2**), and spring **406**(**4**) having one end attached to the proof mass **402**(**2**) and an opposing end attached to anchor **404**(**2**).

FIG. **5** illustrates additional details for components of a MEMS gyroscope device in which the disclosure is implemented, such as for an actuator **122**, anchor structure **118**, and linking structure **120**. While components relative to proof mass **106**(**2**) are shown and discussed in connection with FIG. **5**, such discussion is also applicable to the components relative to the other proof mass **106**(**1**).

Actuator **122**(**2**) is configured to produce drive motion for proof mass **106**(**2**) at a drive frequency, such as by converting an electrical signal into physical or mechanical movement. For example, actuator **122**(**2**) is a capacitive mechanism, such as a comb drive having moving combs (illustrated as attached to the interior sidewalls of openings in actuator frame **522**) and static combs (illustrated inside of the openings in actuator frame **522**) that use electrostatic forces to generate mechanical movement or vibration. The dual static combs provide drive motion in a positive and negative drive direction (illustrated as D+ and D−), which is in the X-directional axis. Actuator frame **522** is also coupled to anchors **520**(**1**)-(**4**) formed on the substrate via springs **518**(**1**)-(**4**), which couple actuator **122**(**2**) to the substrate while allowing drive motion generation.

Proof mass **106**(**2**) is coupled to anchor structure **118**(**2**), which includes an anchor **510**(**2**) formed on the substrate, a bar **516** having one end coupled to proof mass **106**(**2**) by spring **504**(**3**) and an opposing end coupled to anchor **510**(**2**) by spring **504**(**4**). Proof mass **106**(**2**) is also coupled to linking structure **120**(**1**), which includes horizontal bar **502** and vertical bar **512**. One end of horizontal bar **502** is coupled to an outer side of proof mass **106**(**2**) by spring **504**(**1**), and an opposing end of horizontal bar **502** is coupled to an end of vertical bar **512**. An opposing end of vertical bar **512** is coupled to actuator **122**(**2**) by spring or flexible bar **514**. A mid-point of linking structure **120**(**1**), such as near the illustrated junction of the horizontal bar **502** and vertical bar **512**, is coupled by spring **504**(**2**) to anchor **510**(**1**) formed on the substrate. Drive motion produced by actuator **122**(**2**) in the X-directional axis is transmitted to linking structure **120**(**1**), which pivots around anchor **510**(**1**) and translates the drive motion into the Y-directional axis to proof mass **106**(**2**).

Sense electrode **506** (illustrated as a box with broken lines) is formed on the surface of the substrate and underlies proof mass **106**(**2**). Sense electrode **506** is configured to detect sense movement in the Z-directional axis. It is noted that actuators **122**(**1**) and **122**(**2**) are configured to generate movement that results in anti-phase drive motion of proof masses **106**(**1**) and **106**(**2**) to slide past one another in the Y-directional axis, where proof masses **106**(**1**) and (**2**) also move toward and away from underlying sense electrodes in anti-phase sense motion (e.g., proof mass **106**(**1**) moves toward its underlying sense electrode while proof mass **106**(**2**) moves away from its underlying sense electrode).

FIG. **6** illustrates additional details for components of a MEMS gyroscope device in which the disclosure is implemented, such as for an actuator **128**, sense structure **138**, linking structure **140**, and isolating structure **146**. While components relative to proof mass **108**(**2**) are shown and discussed in connection with FIG. **6**, such discussion is also applicable to the components relative to the other proof mass **108**(**1**).

Actuator **128**(**2**) is configured to produce drive motion for proof mass **108**(**2**) at a drive frequency, similar to actuator **122**(**2**), as discussed above in connection with FIG. **5**. In the embodiment shown, actuator **128**(**2**) is a comb drive that produces drive motion in the X-directional axis. Actuator frame **628** is coupled to anchors **614**(**1**)-(**4**) via springs **616**(**1**)-(**4**), which couple actuator **128**(**2**) to the substrate while allowing drive motion generation.

Proof mass **108**(**2**) is coupled to linking structure **140**(**3**), which includes a horizontal bar **602**(**1**) having one end coupled to proof mass **108**(**2**) by spring **604**(**1**) and an opposing end coupled to vertical bar **610**(**1**), which in turn is coupled to actuator frame **628** by spring or flexible bar **612**(**1**). Proof mass **108**(**2**) is also coupled to linking structure **140**(**4**), which includes horizontal bar **602**(**2**) having one end coupled to proof mass **108**(**2**) by spring **604**(**2**) and an opposing end coupled to vertical bar **610**(**2**), which in turn is coupled to actuator frame **628** by spring or flexible bar **612**(**2**). Drive motion produced by actuator **128**(**2**) in the X-directional axis is transmitted to linking structures **140** (**3**)-(**4**), which in turn transmits the drive motion in the X-directional axis to proof mass **108**(**2**).

Sense electrode **608** (illustrated as a box with broken lines) is formed on the surface of the substrate and underlies proof mass **108**(**2**). Sense electrode **608** is configured to detect sense movement in the Z-directional axis. It is noted that actuators **128**(**1**) and **128**(**2**) are configured to generate movement that results in anti-phase drive motion of proof masses **108**(**1**) and **108**(**2**) to move toward and away from another in the X-directional axis (e.g., tuning fork motion), where proof masses **108**(**1**) and (**2**) also move toward and away from underlying sense electrodes in anti-phase sense motion (e.g., proof mass **108**(**1**) moves toward its underlying sense electrode while proof mass **108**(**2**) moves away from its underlying sense electrode).

Proof mass **108**(**2**) is also coupled to a sense frame **626** of sense structure **138**(**2**) by isolating structures **146**(**3**)-(**4**). Isolating structure **146**(**3**) includes vertical bar **620**(**1**) having one end coupled to proof mass **108**(**2**) by spring **618**(**1**) and an opposing end coupled to an outer wall of sense frame **626** that is closest to proof mass **108**(**2**) by spring **618**(**2**). Isolating structure **146**(**4**) includes vertical bar **620**(**2**) having one end coupled to proof mass **108**(**2**) by spring **618**(**4**) and an opposing end coupled to the outer wall of sense frame **626** by spring **618**(**3**). These isolating structures **146**(**3**)-(**4**) transfer sense motion from proof mass **108**(**2**) in the Y-directional axis to sense frame **626**, but minimize the transfer of sense motion from proof mass **108**(**2**) in the Z-directional axis to sense frame **626**. In other words, isolating structures **146**(**3**)-(**4**) reduce coupling of the sense motion of proof mass **108**(**2**) in the Z-directional axis. Isolating structures **146**(**3**)-(**4**) also minimize the transfer of drive motion from proof mass **108**(**2**) in the X-directional axis to sense frame **626**.

Sense frame **626** includes a number of openings that extend through top and bottom surfaces of sense frame **626**. An anchor **622**(**1**) is coupled to an interior sidewall of one opening in sense frame **626** by spring **624**(**1**), and anchor **622**(**2**) is coupled to an interior sidewall of another opening in sense frame **626** by spring **624**(**2**).

The remaining openings of sense frame **626** each surround a pair of sense electrodes that detect motion in positive and negative directions of the Y-directional axis (illustrated as S+ and S−). Each pair of sense electrodes are formed on the surface of the substrate and extend through an opening in sense frame **626**. The pair of electrodes are separated from one another by a spacing distance and separated from interior sidewalls of the opening by a sense distance, which changes as the sense motion shifts the sense frame in positive and negative directions in the Y-directional axis.

FIG. **7** illustrates a top-down view of anti-phase drive motion of proof masses **106**(**1**)-(**2**) in the Y-directional axis (e.g., in opposite directions of the Y-directional axis). In the top portion of FIG. **7**, proof mass **106**(**1**) is moving in a positive direction, while proof mass **106**(**2**) is moving in a negative direction. In the bottom portion of FIG. **7**, proof mass **106**(**1**) is moving in a negative direction, while proof mass **106**(**2**) is moving in a positive direction. In this manner, proof masses **106**(**1**) and **106**(**2**) slides past one another in the Y-directional axis. The dotted line indicates a central axis common to both proof masses **106**(**1**)-(**2**) when at rest. The dotted line also indicates a cross-sectional view for FIGS. **8** and **9**.

FIG. **8** illustrates a cross-sectional view of proof masses **106**(**1**)-(**2**), where the Y-directional axis is now shown as going into the page. When proof masses **106**(**1**)-(**2**) do not experience rotation while being driven, proof masses **106** (**1**)-(**2**) slide in the Y-directional axis while maintaining a distance **812** above and parallel to their respective sense electrodes **506**(**1**)-(**2**), which are formed on substrate **810**.

FIG. **9** illustrates a cross-sectional view of anti-phase sense motion of proof masses **106**(**1**)-(**2**) in the Z-directional axis (e.g., in opposite directions of the Z-directional axis). When proof masses **106**(**1**)-(**2**) experience rotation in the X-directional axis while being driven, proof masses **106**(**1**)-(**2**) move in a sense direction orthogonal to the drive direction and the rotation direction, which is in the Z-directional axis in this embodiment.

In the top portion of FIG. **9**, proof mass **106**(**1**) is moving in a negative direction toward sense electrode **506**(**1**), which shortens the sense distance **814** between proof mass **106**(**1**) and sense electrode **506**(**1**). Proof mass **106**(**2**) is moving in a positive direction away from sense electrode **506**(**2**), which lengthens the sense distance **816** between proof mass **106**(**2**) and sense electrode **506**(**2**). It is noted that proof masses **106**(**1**)-(**2**) remain substantially parallel to the surface of the substrate **810** and to the sense electrodes **506**(**1**)-(**2**) during the anti-phase sense motion, which improves the efficiency of sense detection (e.g., detecting changing capacitance) by sense electrodes **506**(**1**)-(**2**).

In the bottom portion of FIG. **9**, proof mass **106**(**1**) is moving in a positive direction away from sense electrode **506**(**1**), which lengthens the sense distance **818** between proof mass **106**(**1**) and sense electrode **506**(**1**). Proof mass **106**(**2**) is moving in a negative direction toward sense electrode **506**(**2**), which shortens the sense distance **820** between proof mass **106**(**2**) and sense electrode **506**(**2**).

FIG. **10** illustrates a top-down view of anti-phase drive motion of proof masses **108**(**1**)-(**2**) in the X-directional axis (e.g., in opposite directions of the X-directional axis). Proof mass **108**(**1**) is coupled to sense frame **626**(**1**) and proof mass **108**(**2**) is coupled to sense frame **626**(**2**), as discussed above in connection with FIG. **6**. An example opening **1012**(**1**) is illustrated in sense frame **626**(**1**), which surrounds a pair of sense electrodes S+ and S−. An example opening **1012**(**2**) is illustrated in sense frame **626**(**2**), which surrounds a pair of sense electrodes S+ and S−. Sense electrodes S+ and S− are separated from one another by a spacing distance Ds in the Y-directional axis. Each pair of sense electrodes extend up from the underlying substrate through respective openings **1012**(**1**)-(**2**).

Opening **1012**(**1**) has a sidewall opposite a sensing surface of sense electrode S+ that is parallel to the X-directional axis, where this sidewall is referred to as an S+ sidewall of opening **1012**(**1**). The S+ sidewall may also be referred to as a sidewall that is closest to sense electrode S+. The distance between the S+ sidewall and sense electrode S+ is also referred to as an S+ sense distance. Opening **1012**(**1**) has another sidewall opposite a sensing surface of sense electrode S− that is parallel to the X-directional axis, where this sidewall is referred to as an S− sidewall of opening **1012**(**1**). The S− sidewall may also be referred to as a sidewall closest to sense electrode S−. The distance between the S-sidewall and sense electrode S− is also referred to as an S− sense distance. It is noted that the S+ and S− sidewalls of opening **1012**(**1**) are opposite one another.

In the top portion of FIG. **10**, proof mass **108**(**1**) is moving in a positive direction (e.g., to the right), while proof mass **108**(**2**) is moving in a negative direction (e.g., to the left). In the bottom portion of FIG. **10**, proof mass **108**(**1**) is moving in a negative direction, while proof mass **108**(**2**) is moving in a positive direction. In this manner, proof masses **108**(**1**) and **108**(**2**) move toward and away from one another in the X-directional axis. The dotted line indicates a cross-sectional view for FIGS. **11** and **12**. Since sense frames **626** (**1**)-(**2**) are coupled to sense motion of respective proof masses **108**(**1**)-(**2**) in the Y-directional axis and decoupled from drive motion in the X-directional axis (and are also decoupled from sense motion of respective proof masses **108**(**1**)-(**2**) in the Z-directional axis), a same sense distance **1010** is maintained between each sense electrode and sidewall of openings **1012**(**1**)-(**2**).

FIG. **11** illustrates a cross-sectional view of proof masses **108**(**1**)-(**2**), where the Y-directional axis is now shown as going into the page. When proof masses **108**(**1**)-(**2**) do not experience rotation while being driven, proof masses **108** (**1**)-(**2**) move in the X-directional axis while maintaining a distance **1112** above and parallel to their respective sense electrodes **608**(**1**)-(**2**), which are formed on substrate **810**.

FIG. **12** illustrates a cross-sectional view of anti-phase sense motion of proof masses **108**(**1**)-(**2**) in the Z-directional axis (e.g., in opposite directions of the Z-directional axis). Proof masses **108**(**1**)-(**2**) continue to move toward and away from one another in the X-directional axis as shown in FIG. **10**, but such drive motion is not illustrated in FIG. **12** in order to simplify description of the sense motion.

When proof masses **108**(**1**)-(**2**) experience rotation in the Y-directional axis while being driven, proof masses **108**(**1**)-(**2**) move in a sense direction orthogonal to the drive direction and the rotation direction, which is in the Z-directional axis in this embodiment. In the top portion of FIG. **12**, proof mass **108**(**1**) is moving in a negative direction toward sense electrode **608**(**1**), which shortens the sense distance **1114** between proof mass **108**(**1**) and sense electrode **608**(**1**). Proof mass **106**(**2**) is moving in a positive direction away from sense electrode **608**(**2**), which lengthens the sense distance **1116** between proof mass **108**(**2**) and sense electrode **608**(**2**). It is noted that proof masses **108**(**1**)-(**2**) remain substantially parallel to the surface of the substrate **810** and to the sense electrodes **608**(**1**)-(**2**) during the anti-phase sense motion, which improves the efficiency of sense detection (e.g., detecting changing capacitance) by sense electrodes **608**(**1**)-(**2**).

In the bottom portion of FIG. **12**, proof mass **108**(**1**) is moving in a positive direction away from sense electrode **608**(**1**), which lengthens the sense distance **1118** between proof mass **108**(**1**) and sense electrode **608**(**1**). Proof mass **108**(**2**) is moving in a negative direction toward sense electrode **608**(**2**), which shortens the sense distance **1120** between proof mass **108**(**2**) and sense electrode **608**(**2**).

FIG. **13** illustrates a top-down view of anti-phase sense motion of proof masses **108**(**1**)-(**2**) in the Y-directional axis (e.g., in opposite directions of the Y-directional axis). Proof masses **108**(**1**)-(**2**) continue to move toward and away from one another in the X-directional axis as shown in FIG. **10**, but such drive motion is not illustrated in FIG. **13** in order to simply description of the sense motion.

When proof masses **108**(**1**)-(**2**) experience rotation in the Z-directional axis while being driven, proof masses **108**(**1**)-(**2**) move in a sense direction orthogonal to the drive direction and the rotation direction, which is in the Y-directional axis in this embodiment. In the top portion of FIG. **13**, proof mass **108**(**1**) is moving in a negative direction of the Y-directional axis. Since sense motion of proof mass **108**(**1**) is coupled to sense frame **626**(**1**), sense frame **626**(**1**) also moves in the negative direction. Opening **1012**(**1**) is similarly shifted in the negative direction and moves the S+ sidewall toward sense electrode S+, which shortens the S+ sense distance **1314** between the S+ sidewall and sense electrode S+. Simultaneously, the S− sidewall moves away from sense electrode S−, which lengthens the S− sense distance **1316** between the S− sidewall and sense electrode S−. Proof mass **108**(**2**) is moving in a positive direction of the Y-directional axis, which also moves sense frame **626**(**2**) in the positive direction since sense motion of proof mass **108**(**2**) is coupled to sense frame **626**(**2**). Opening **1012**(**2**) is similarly shifted in the positive direction and moves the S+ sidewall away from sense electrode S+, which lengthens the S+ sense distance **1318** between the S+ sidewall and sense electrode S+. Simultaneously, the S− sidewall moves toward sense electrode S−, which shortens the S− sense distance **1320** between the S-sidewall and sense electrode S−.

In the bottom portion of FIG. **13**, proof mass **108**(**1**) is moving in a positive direction of the Y-directional axis, which also shifts opening **1012**(**1**) in the positive direction. The S+ sidewall moves away from sense electrode S+ and the S− sidewall moves toward sense electrode S−, which lengthens the S+ sense distance **1322** and shortens the S− sense distance **1324**. Proof mass **108**(**2**) is moving in a negative direction of the Y-directional axis, which also shifts opening **1012**(**2**) in the negative direction. The S+ sidewall moves toward sense electrode S+ and the S− sidewall moves away from sense electrodes S−, which shortens the S+ sense distance **1326** and lengthens the S− sense distance **1328**.

By now it should be appreciated that there has been provided embodiments of a MEMS gyroscope device that is movable in three axes to measure angular velocity in three axes, which includes a first pair of proof masses that each have a recess to which a pivot structure is coupled, the first pair of proof masses are driven to slide back and forth past one another in a first in-plane directional axis (e.g., in the Y-directional axis), and a second pair of proof masses that each have a recess to which another pivot structure is coupled, the second pair of proof masses are driven to move toward and away from one another (e.g., tuning fork vibration) in a second in-plane directional axis (e.g., in the X-directional axis) perpendicular to the first in-plane directional axis.

In one embodiment of the present disclosure, a microelectromechanical system (MEMS) gyroscope device is provided, which includes: a substrate having a surface parallel to a plane; a first proof mass and a second proof mass positioned in space above the surface of the substrate and driven to slide back and forth past one another in a first directional axis of the plane, wherein the first proof mass has a first recess in a side closest to the second proof mass, and the second proof mass has a second recess in a side closest to the first proof mass; a first pivot structure having one end coupled to the first proof mass within the first recess and an opposite end coupled to the second proof mass within the second recess; a first anchor on the surface of the substrate, the first anchor located between the first and second recesses and coupled to a mid-point of the first pivot structure; and a third proof mass and a fourth proof mass positioned in space above the surface of the substrate and driven to move toward and away from one another in a second directional axis of the plane that is perpendicular to the first directional axis; wherein the first and second proof masses move in a third directional axis that is normal to the plane in response to angular velocity in the second directional axis, and the third and fourth proof masses move in the third directional axis in response to angular velocity in the first directional axis.

One aspect of the above embodiment provides that the third and fourth proof masses move in the first directional axis in response to angular velocity in the third directional axis.

Another aspect of the above embodiment provides that the MEMS device further includes: a first actuator and a second actuator respectively coupled to the first and second proof masses and respectively configured to drive the first and second proof masses in opposite directions of the first directional axis; and a third actuator and a fourth actuator respectively coupled to the third and fourth proof masses and respectively configured to drive the third and fourth proof masses in opposite directions of the second directional axis.

A further aspect of the above embodiment provides that the MEMS device further includes: a first drive motion linking structure coupled to the first and third actuators, the first drive motion linking structure configured to couple drive motion provided by the first and third actuators; and a second drive motion linking structure coupled to the second and fourth actuators, the second drive motion linking structure configured to couple drive motion provided by the second and fourth actuators.

Another aspect of the above embodiment provides that a same drive frequency is utilized to drive the first, second, third, and fourth proof masses.

Another aspect of the above embodiment provides that the first pivot structure includes: a first pivot bar having a mid-point coupled to the first anchor by a first spring, a first end coupled to a first sidewall of the first recess of the first proof mass by a second spring, and a second end coupled to a first sidewall of the second recess of the second proof mass by a third spring, and a second pivot bar having a mid-point coupled to the first anchor by a fourth spring, a first end coupled to a second sidewall of the first recess of the first proof mass by a fifth spring, and a second end coupled to a second sidewall of the second recess of the second proof mass by a sixth spring.

Another aspect of the above embodiment provides that the first pivot structure is configured to move flexibly about the first anchor in the first directional axis and in the third directional axis, wherein opposite ends of the first pivot structure are configured to move in opposite directions in the first directional axis and are configured to move in opposite directions in the third directional axis.

Another aspect of the above embodiment provides that the MEMS device further includes: a second pivot structure, wherein the third proof mass has a third recess in a side closest to the fourth proof mass, and the fourth proof mass has a fourth recess in a side closest to the third proof mass, and the second pivot structure has one end coupled to the third proof mass within the third recess and an opposite end coupled to the fourth proof mass within the fourth recess; and a second anchor on the surface of the substrate, the second anchor located between the third and fourth recesses and coupled to a mid-point of the second pivot structure.

A further aspect of the above embodiment provides that the second pivot structure includes: a first pivot bar having a mid-point coupled to the second anchor by a first spring, a first end coupled to a first sidewall of the third recess of the third proof mass by a second spring, and a second end coupled to a first sidewall of the fourth recess of the fourth proof mass by a third spring, and a second pivot bar having a mid-point coupled to the second anchor by a fourth spring, a first end coupled to a second sidewall of the third recess of the third proof mass by a fifth spring, and a second end coupled to a second sidewall of the fourth recess of the fourth proof mass by a sixth spring.

Another further aspect of the above embodiment provides that the second pivot structure includes: a first pivot bar having a mid-point coupled to the anchor by a first spring, a first end coupled to a first linking structure by a second spring, and a second end coupled to a second linking structure by a third spring, a second pivot bar having a mid-point coupled to the anchor by a fourth spring, a first end coupled to the first linking structure by a fifth spring, and a second end coupled to the second linking structure by a sixth spring, the first linking structure coupled to the third proof mass within the third recess by a first plurality of springs, and the second linking structure coupled to the fourth proof mass within the fourth recess by a second plurality of springs.

Another aspect of the above embodiment provides that the MEMS device further includes: a common mode drive spring structure between the third and fourth proof masses, the common mode drive spring structure including: a second anchor, a first spring having one end coupled to the second anchor and another end coupled to the third proof mass, and a second spring having one end coupled to the second anchor and another end coupled to the fourth proof mass.

Another aspect of the above embodiment provides that the MEMS device further includes: a first linking structure coupled between the second proof mass and an actuator, the first linking structure includes an L-shaped bar, a mid-section of the L-shaped bar coupled to a second anchor near a corner of the second proof mass on a side of the second proof mass farthest away from the first proof mass, one end of the L-shaped bar coupled to the second proof mass by a first spring and an opposite end of the L-shaped bar coupled to the actuator by a second spring, the actuator configured to provide drive motion in the second directional axis and the first linking structure configured to flexibly pivot about the second anchor and move the second proof mass in the first directional axis.

Another aspect of the above embodiment provides that the MEMS device further includes: a first sense electrode and a second sense electrode on the surface of the substrate and respectively underneath and separated from the first and second proof masses by first and second distances in the third directional axis, and a third sense electrode and a fourth sense electrode on the surface of the substrate and respectively underneath and separated from the third and fourth proof masses by third and fourth distances in the third directional axis.

A further aspect of the above embodiment provides that the first and second proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the second directional axis, and the first and second proof masses remain substantially in parallel with the first and second sense electrodes as the first and second proof masses respectively move toward and away from the first and second electrodes in response to the angular velocity in the second directional axis.

Another further aspect of the above embodiment provides that the third and fourth proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the first directional axis, and the third and fourth proof masses remain substantially in parallel with the third and fourth sense electrodes as the third and fourth proof masses respectively move toward and away from the third and fourth electrodes in response to the angular velocity in the first directional axis.

Another aspect of the above embodiment provides that the MEMS device further includes: an actuator coupled to the fourth proof mass by a first linking bar and a second linking bar; a sense frame coupled to the fourth proof mass by a first isolating bar and a second isolating bar, wherein the first and second linking bars do not contact the sense frame, and the sense frame is isolated from drive motion provided by the actuator; and a first sense electrode and a second sense electrode on the surface of the substrate, separated from one another by a spacing distance in the first directional axis, the first and second electrodes extend through an opening in the sense frame, wherein the first and second sense electrodes are respectively separated from a first and second sidewall of the opening by a first and second distance in the first directional axis, the second sidewall is opposite the first sidewall.

Another aspect of the above embodiment provides that the first, second, third, and fourth proof masses lie in a common plane that is parallel to the surface of the substrate, the first proof mass has a first side that is closest to the second proof mass and a second side that is closest to the third proof mass, the second side is perpendicular to the first side in the common plane, and the fourth proof mass has a third side that is closest to the third proof mass and a fourth side that is closest to the second proof mass, the fourth side is perpendicular to the first side in the common plane.

In another embodiment of the present disclosure a method for operating a microelectromechanical system (MEMS) gyroscope device is provided, the method including: driving a first pair of proof masses of the gyroscope to slide back and forth past one another in a first directional axis of a plane parallel to a surface of a substrate of the gyroscope, wherein the first pair of proof masses each have a respective recess, a respective end of a pivot structure is coupled to each of the first pair of proof masses within the respective recess, and a mid-point of the pivot structure is coupled to an anchor between the respective recesses; driving a second pair of proof masses of the gyroscope to move toward and away from one another in a second directional axis of the plane that is perpendicular to the first directional axis; in response to angular velocity experienced by the first pair of proof masses in the second directional axis, detecting movement of the first pair of proof masses in a third directional axis that is normal to the plane; and in response to angular velocity experienced by the second pair of proof masses in the first directional axis, detecting movement of the second pair of proof masses in the third directional axis.

One aspect of the above embodiment provides that the method further includes: in response to angular velocity experienced by the second pair of proof masses in the third directional axis, detecting movement of the second pair of proof masses in the first directional axis.

Another aspect of the above embodiment provides that the first pair of proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the second directional axis, the first pair of proof masses remain substantially in parallel with a first pair of sense electrodes as the first pair of proof masses respectively move toward and away from the first pair of sense electrodes in response to the angular velocity in the second directional axis, the second pair of proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the first directional axis, and the second pair of proof masses remain substantially in parallel with a second pair of sense electrodes as the second pair of proof masses respectively move toward and away from the second pair of sense electrodes in response to the angular velocity in the first directional axis.

Because the apparatus implementing the present invention is, for the most part, composed of electronic components and circuits known to those skilled in the art, circuit details will not be explained in any greater extent than that considered necessary as illustrated above, for the understanding and appreciation of the underlying concepts of the present invention and in order not to obfuscate or distract from the teachings of the present invention.

Moreover, the terms "front," "back," "top," "bottom," "over," "under" and the like in the description and in the claims, if any, are used for descriptive purposes and not necessarily for describing permanent relative positions. It is understood that the terms so used are interchangeable under appropriate circumstances such that the embodiments of the invention described herein are, for example, capable of operation in other orientations than those illustrated or otherwise described herein.

As used herein the terms "substantial" and "substantially" mean sufficient to accomplish the stated purpose in a practical manner and that minor imperfections, if any, are not significant for the stated purpose.

Although the invention is described herein with reference to specific embodiments, various modifications and changes can be made without departing from the scope of the present invention as set forth in the claims below. For example, additional or fewer proof masses may be implemented in the MEMS gyroscope device of FIG. **1** in other embodiments, the drive motion linking structures may be present or absent in other embodiments, and the common mode drive spring structures may be present or absent in other embodiments. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope of the present invention. Any benefits, advantages, or solutions to problems that are described herein with regard to specific embodiments are not intended to be construed as a critical, required, or essential feature or element of any or all the claims.

The term "coupled," as used herein, is not intended to be limited to a direct coupling or a mechanical coupling.

Furthermore, the terms "a" or "an," as used herein, are defined as one or more than one. Also, the use of introductory phrases such as "at least one" and "one or more" in the claims should not be construed to imply that the introduction of another claim element by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim element to inventions containing only one such element, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an." The same holds true for the use of definite articles.

Unless stated otherwise, terms such as "first" and "second" are used to arbitrarily distinguish between the elements such terms describe. Thus, these terms are not necessarily intended to indicate temporal or other prioritization of such elements.

What is claimed is:

1. A microelectromechanical system (MEMS) gyroscope device comprising:

a substrate having a surface parallel to a plane;

a first proof mass and a second proof mass positioned in space above the surface of the substrate and driven to slide back and forth past one another in a first directional axis of the plane, wherein

the first proof mass has a first recess in a side closest to the second proof mass, and

the second proof mass has a second recess in a side closest to the first proof mass;

a first pivot structure having one end coupled to the first proof mass within the first recess and an opposite end coupled to the second proof mass within the second recess;

a first anchor on the surface of the substrate, the first anchor located between the first and second recesses and coupled to a mid-point of the first pivot structure; and

a third proof mass and a fourth proof mass positioned in space above the surface of the substrate and driven to move toward and away from one another in a second directional axis of the plane that is perpendicular to the first directional axis;

wherein

the first and second proof masses move in a third directional axis that is normal to the plane in response to angular velocity in the second directional axis, and

the third and fourth proof masses move in the third directional axis in response to angular velocity in the first directional axis;

a first actuator and a second actuator respectively coupled to the first and second proof masses and respectively configured to drive the first and second proof masses in opposite directions of the first directional axis;

a third actuator and a fourth actuator respectively coupled to the third and fourth proof masses and respectively configured to drive the third and fourth proof masses in opposite directions of the second directional axis;

a first drive motion linking structure coupled to the first and third actuators, the first drive motion linking structure configured to couple drive motion provided by the first and third actuators; and

a second drive motion linking structure coupled to the second and fourth actuators, the second drive motion linking structure configured to couple drive motion provided by the second and fourth actuators.

2. The MEMS device of claim **1**, wherein

the third and fourth proof masses move in the first directional axis in response to angular velocity in the third directional axis.

3. The MEMS device of claim **1**, wherein a same drive frequency is utilized to drive the first, second, third, and fourth proof masses.

4. The MEMS device of claim **1**, wherein

the first pivot structure comprises:

a first pivot bar having a mid-point coupled to the first anchor by a first spring, a first end coupled to a first sidewall of the first recess of the first proof mass by a second spring, and a second end coupled to a first sidewall of the second recess of the second proof mass by a third spring, and

a second pivot bar having a mid-point coupled to the first anchor by a fourth spring, a first end coupled to a second sidewall of the first recess of the first proof mass by a fifth spring, and a second end coupled to a second sidewall of the second recess of the second proof mass by a sixth spring.

5. The MEMS device of claim **1**, wherein

the first pivot structure is configured to move flexibly about the first anchor in the first directional axis and in the third directional axis, wherein opposite ends of the first pivot structure are configured to move in opposite directions in the first directional axis and are configured to move in opposite directions in the third directional axis.

6. The MEMS device of claim **1**, further comprising:

a second pivot structure, wherein

the third proof mass has a third recess in a side closest to the fourth proof mass, and

the fourth proof mass has a fourth recess in a side closest to the third proof mass, and

the second pivot structure has one end coupled to the third proof mass within the third recess and an opposite end coupled to the fourth proof mass within the fourth recess; and

a second anchor on the surface of the substrate, the second anchor located between the third and fourth recesses and coupled to a mid-point of the second pivot structure.

7. The MEMS device of claim **6**, wherein

the second pivot structure comprises:

a first pivot bar having a mid-point coupled to the second anchor by a first spring, a first end coupled to a first sidewall of the third recess of the third proof mass by a second spring, and a second end coupled to a first sidewall of the fourth recess of the fourth proof mass by a third spring, and

a second pivot bar having a mid-point coupled to the second anchor by a fourth spring, a first end coupled to a second sidewall of the third recess of the third proof mass by a fifth spring, and a second end coupled to a second sidewall of the fourth recess of the fourth proof mass by a sixth spring.

8. The MEMS device of claim **6**, wherein

the second pivot structure comprises:

a first pivot bar having a mid-point coupled to the anchor by a first spring, a first end coupled to a first linking structure by a second spring, and a second end coupled to a second linking structure by a third spring,

a second pivot bar having a mid-point coupled to the anchor by a fourth spring, a first end coupled to the first linking structure by a fifth spring, and a second end coupled to the second linking structure by a sixth spring,

the first linking structure coupled to the third proof mass within the third recess by a first plurality of springs, and

the second linking structure coupled to the fourth proof mass within the fourth recess by a second plurality of springs.

9. The MEMS device of claim **1**, further comprising:

a common mode drive spring structure between the third and fourth proof masses, the common mode drive spring structure comprising:

a second anchor,

a first spring having one end coupled to the second anchor and another end coupled to the third proof mass, and

a second spring having one end coupled to the second anchor and another end coupled to the fourth proof mass.

10. The MEMS device of claim **1**, further comprising:

a first linking structure coupled between the second proof mass and an actuator, the first linking structure comprises an L-shaped bar, a mid-section of the L-shaped bar coupled to a second anchor near a corner of the second proof mass on a side of the second proof mass farthest away from the first proof mass, one end of the L-shaped bar coupled to the second proof mass by a first spring and an opposite end of the L-shaped bar coupled to the actuator by a second spring, the actuator configured to provide drive motion in the second directional axis and the first linking structure configured to flexibly pivot about the second anchor and move the second proof mass in the first directional axis.

11. The MEMS device of claim **1**, further comprising:

a first sense electrode and a second sense electrode on the surface of the substrate and respectively underneath and separated from the first and second proof masses by first and second distances in the third directional axis, and

a third sense electrode and a fourth sense electrode on the surface of the substrate and respectively underneath and separated from the third and fourth proof masses by third and fourth distances in the third directional axis.

12. The MEMS device of claim **11**, wherein

the first and second proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the second directional axis, and

the first and second proof masses remain substantially in parallel with the first and second sense electrodes as the first and second proof masses respectively move toward and away from the first and second electrodes in response to the angular velocity in the second directional axis.

13. The MEMS device of claim **11**, wherein

the third and fourth proof masses are configured to move in opposite directions in the third directional axis in response to the angular velocity in the first directional axis, and

the third and fourth proof masses remain substantially in parallel with the third and fourth sense electrodes as the third and fourth proof masses respectively move toward and away from the third and fourth electrodes in response to the angular velocity in the first directional axis.

14. The MEMS device of claim **1**, further comprising:

an actuator coupled to the fourth proof mass by a first linking bar and a second linking bar;

a sense frame coupled to the fourth proof mass by a first isolating bar and a second isolating bar, wherein

the first and second linking bars do not contact the sense frame, and

the sense frame is isolated from drive motion provided by the actuator; and

a first sense electrode and a second sense electrode on the surface of the substrate, separated from one another by a spacing distance in the first directional axis, the first and second electrodes extend through an opening in the sense frame, wherein

the first and second sense electrodes are respectively separated from a first and second sidewall of the opening by a first and second distance in the first directional axis, the second sidewall is opposite the first sidewall.

15. The MEMS device of claim **1**, wherein

the first, second, third, and fourth proof masses lie in a common plane that is parallel to the surface of the substrate,

the first proof mass has a first side that is closest to the second proof mass and a second side that is closest to the third proof mass, the second side is perpendicular to the first side in the common plane, and

the fourth proof mass has a third side that is closest to the third proof mass and a fourth side that is closest to the second proof mass, the fourth side is perpendicular to the first side in the common plane.

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